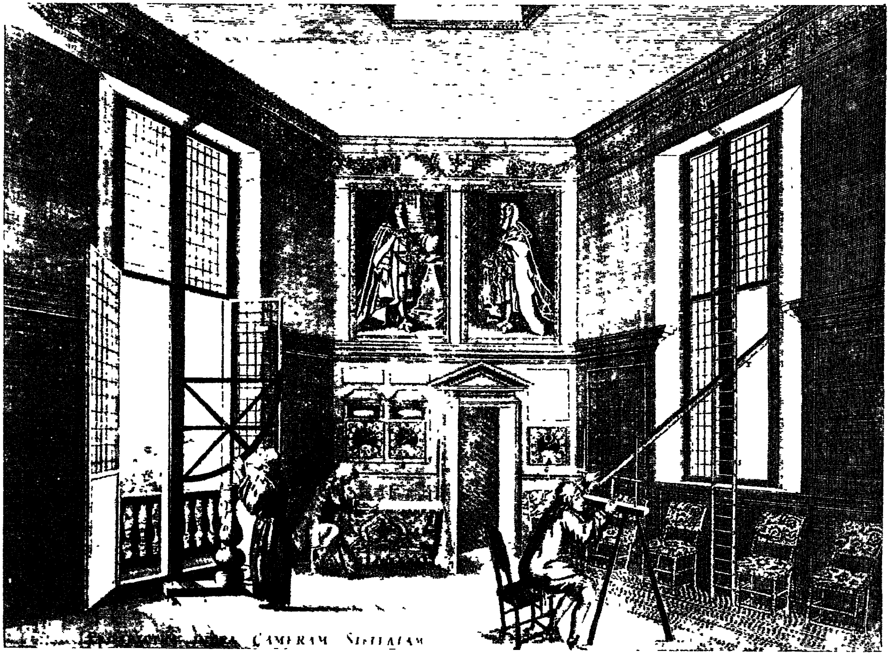
A KEY TO THE STARS

PLATE I



Flamsteed and his assistant, Sharp, observing in the Octagon Room of the Royal Observatory, Greenwich

(*From an old Print*)

E 846

Frontispiece

A KEY TO THE STARS

BY

R. van der RIET WOOLLEY
Former Chief Assistant at the Royal Observatory, Greenwich
John Couch Adams Astronomer. Cambridge University Observatory

BLACKIE & SON LIMITED
LONDON AND GLASGOW

BLACKIE & SON LIMITED
50 Old Bailey, London
17 Stanhope Street, Glasgow
BLACKIE & SON (INDIA) LIMITED
Warwick House, Fort Street, Bombay
BLACKIE & SON (CANADA) LIMITED
Toronto

First Published 1934
Reprinted May 1935
Cheap edition 1939

Printed in Great Britain by Blackie & Son, Ltd., Glasgow

PREFACE

Most professional scientists, judged by their ready criticisms of popular book writing, have views of their own about how a popular book should be written. The author of this one has had a chance to air his views in the exacting field of practice, and he has tried to live up to what he used to preach: that the latest developments, the fields in which speculation is still rife and knowledge has not yet been won for certain, are less suitable for popular exposition than the demonstrable results which are well studied and well known and which partake of the character of the laws of Nature. We do not know that the sun will rise tomorrow and that the constant of universal gravitation will not treble its value next month—but all men order their lives on the assumption that both these things will remain as before. It appears to be equally unlikely that 61 Cygni will exhibit a parallax greater than three-tenths of a second of arc, and so prove me wrong when I maintain that it is 64 million million miles away. In some sense, then, there is certainty in science, and this certain knowledge I have tried to exhibit, argued as well as is possible to a lay reader who has no knowledge of either mathematics or physics.

The author wishes to thank those of his friends who have read through MS. or proofs for their kindly help, and to thank the Astronomer Royal and the Directors of Mount Wilson and Yerkes Observatories for permission to use the material here made into illustrations.

CONTENTS

LIST OF PLATES

A KEY TO THE STARS

CHAPTER I

Time and Longitude

BEFORE I took a regular interest in astronomy, I realized in a vague way that sometimes one can see a well-known constellation (Orion was my favourite, and it still is), and sometimes one cannot: except in the case of " The Plough ", which is always to be seen in the night sky. I was told that the earth moved round the sun once a year, but nobody pointed out to me the connexion between the motion and the appearance and disappearance of certain constellations; but the constellations are spread out all over the sky, and the sun appears to travel right round the sky once a year, those constellations which lie anywhere near the sun's path disappear once a year, simply because one cannot see stars in the daytime since the diffused blue light from the sky masks them. For example, my friend Orion is a winter constellation, but during the summer months the sun's path passes close to Orion, the sun itself actually coming between the earth and the constellation; and when this happens Orion is not to be seen. Near to Orion is the bright star

Sirius, close to which the sun appears to pass in the summer; and the ancients believed that this star heated up the sun, which caused the general heat of the summer. Though we have discarded this belief, we commemorate the annual passage of the sun past Orion's dog (in which constellation Sirius lies) in the phrase, the "dog days" of August.

It is an unfortunate fact that one cannot make a satisfactory map of a spherical surface on a flat piece of paper; one cannot make a map of the world without distorting some parts of it; neither can one make a satisfactory map of the heavens, showing everything at once, without distortion of the distances of one object from another. But the map of the world which shows the equator best is Mercator's projection, and the accompanying three maps (figs. 1*a*, 1*b*, 1*c*) show Mercator's projection of the heavens, with the equator and the ecliptic traced on it. The heavenly equator is the plane of the earth's equator—that is, the points which actually are overhead at the terrestrial equator; and the ecliptic is the path of the centre of the sun on its annual round of the sky. (It is more usual to define the ecliptic as the plane of the earth's orbit round the sun; but it comes to the same thing.) You will notice that the sun's path crosses the equator at two points; this means that the sun is directly overhead on the terrestrial equator twice a year on its path through the heavens. During the summer the sun moves north of the equator and in winter to the south of it, the two points where it crosses the equator being the equinoxes, that is, *points* in the sky; but the *times* at which the sun occupies these points are also spoken of as the equi-

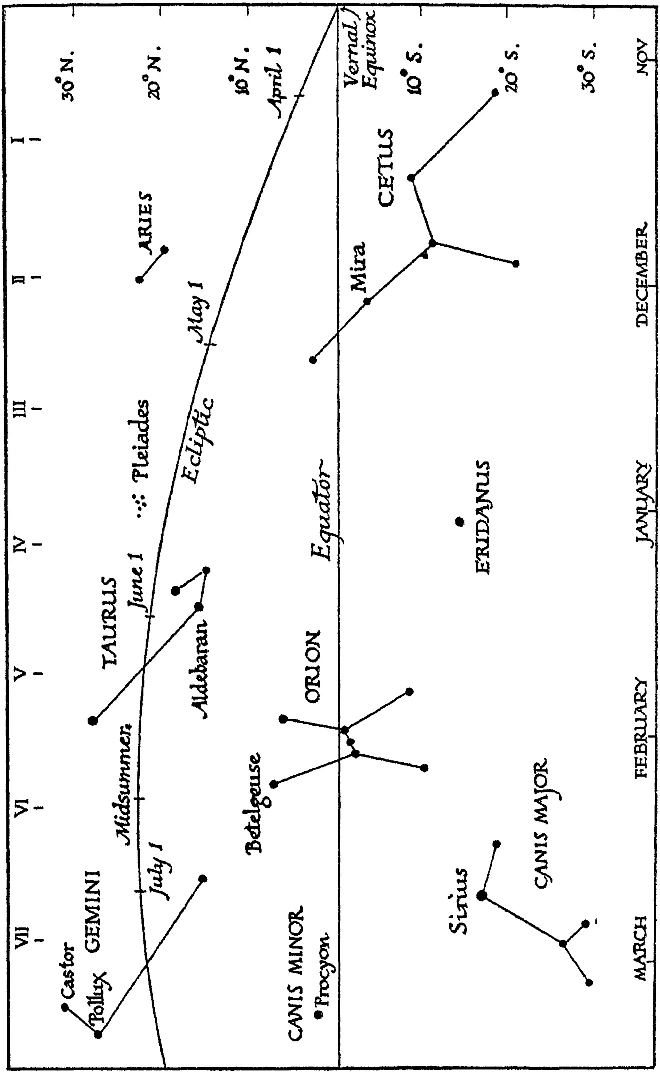

30° N.
20° N.
10° N.
10° S.
20° S.
30° S.
I
II
III
IV
V
VI
VII
NOV
DECEMBER
JANUARY
FEBRUARY
MARCH
April 1
May 1
June 1
Midsummer
July 1
Vernal Equinox
Ecliptic
Equator
ARIES
Pleiades
TAURUS
Aldebaran
GEMINI
Castor
Pollux
CETUS
Mira
ERIDANUS
ORION
Betelgeuse
CANIS MINOR
Procyon
CANIS MAJOR
Sirius

Fig. 1a

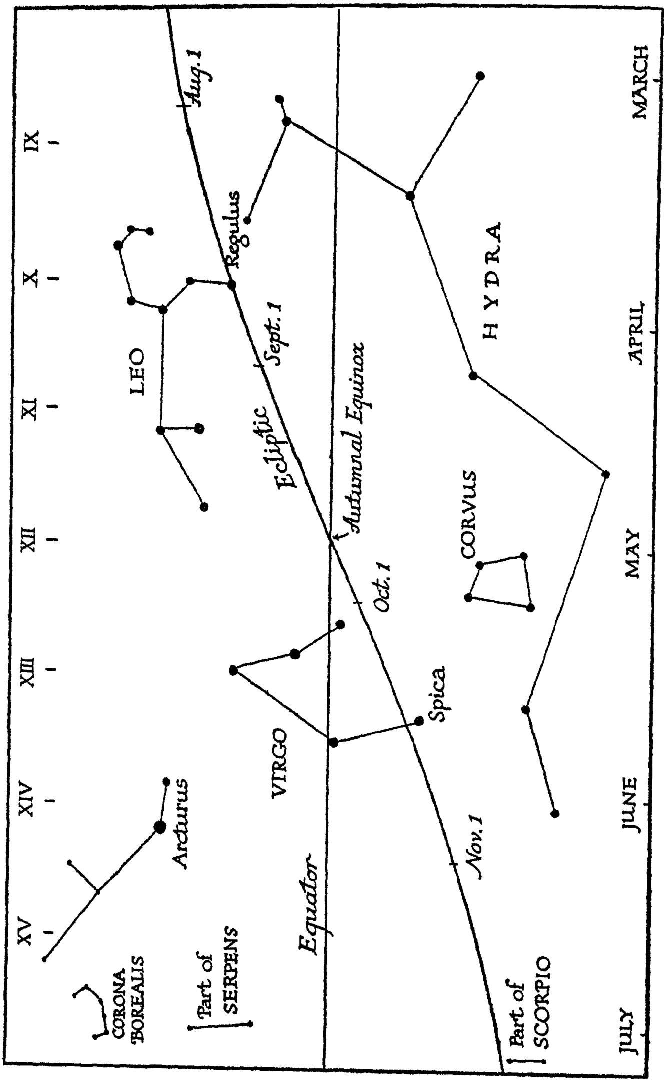

IX
X
XI
XII
XIII
XIV
XV
Aug. 1
Regulus
Sept. 1
Ecliptic
Autumnal Equinox
Oct. 1
Spica
Nov. 1
Equator
LEO
VIRGO
Arcturus
CORONA BOREALIS
Part of SERPENS
HYDRA
CORVUS
Part of SCORPIO
MARCH
APRIL
MAY
JUNE
JULY

Fig. 1b

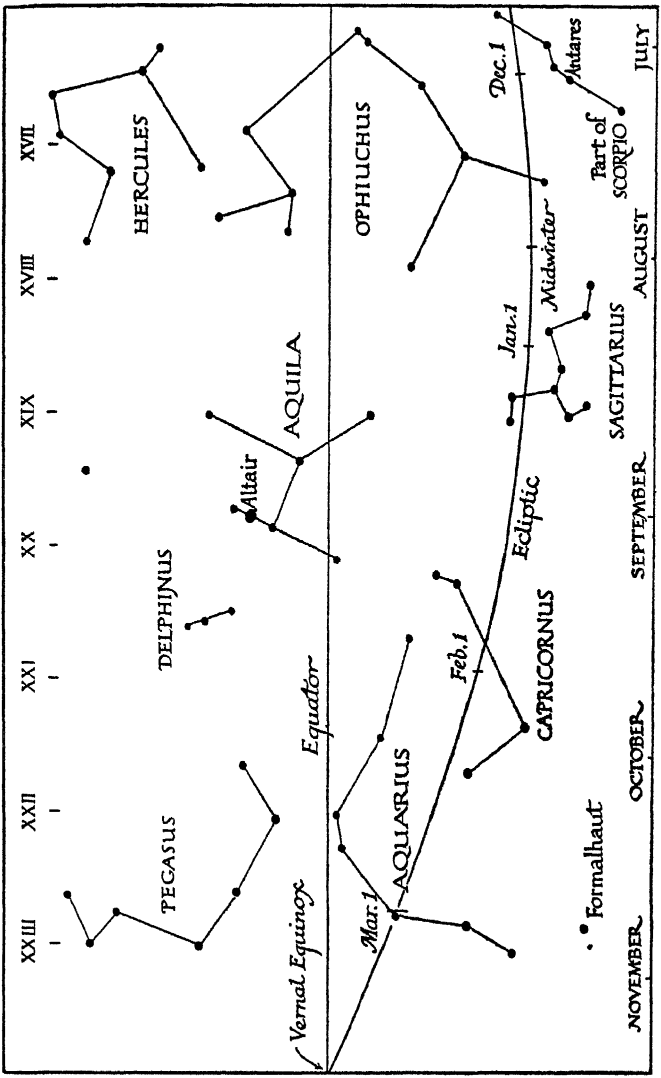

XVII
XVIII
XIX
XX
XXI
XXII
XXIII
HERCULES
OPHIUCHUS
AQUILA
Altair
DELPHINUS
PEGASUS
Equator
Vernal Equinox
AQUARIUS
Mar. 1
Feb. 1
CAPRICORNUS
Ecliptic
Jan. 1
Midwinter
Dec. 1
Antares
Part of SCORPIO
SAGITTARIUS
Formalhaut
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER

Fig. 10

noxes, because at these times both night and day are twelve hours long all over the globe.

The most striking equatorial constellations are marked on these three maps, and some of the brighter and better known stars are named. The dates on the ecliptic are the dates on which the sun arrives at the point indicated, at which time that part of the sky is invisible, and the months marked at the foot of each map are the months during which the corresponding part of the sky crosses the meridian at nine o'clock in the evening, so that the constellations in this part of the sky will be conspicuous in the evening skies. As an example, Orion is below the word Midsummer on the ecliptic, and cannot be seen in June; underneath this constellation is marked February, this being the month in which Orion is due south in the evening at nine o'clock. The Roman numerals mark the hours of Right Ascension, to which we shall refer later.

In addition to the annual motion of the sun round the heavens, there is the rather more obvious and better known daily motion of the sun. The sun rises in the east in the morning, passes across the southern sky (when seen in Great Britain) and sets in the west in the evening. It is not, perhaps, always understood that it carries the whole of the heavens with it, and that the stars rise and set in a similar way, and also the moon. But not all the stars set. The Pole Star does not, neither do stars near the pole, unless you are observing the heavens from somewhere near the terrestrial equator.

Fig. 2 is the map of the north polar regions, plotted out in polar co-ordinates. The most conspicuous polar constellations are the Plough, which is

not itself an official astronomical constellation, but part of the Great Bear, Ursa Major; Cassiopeia, a big W of five bright stars; and Auriga, containing the bright star Capella.

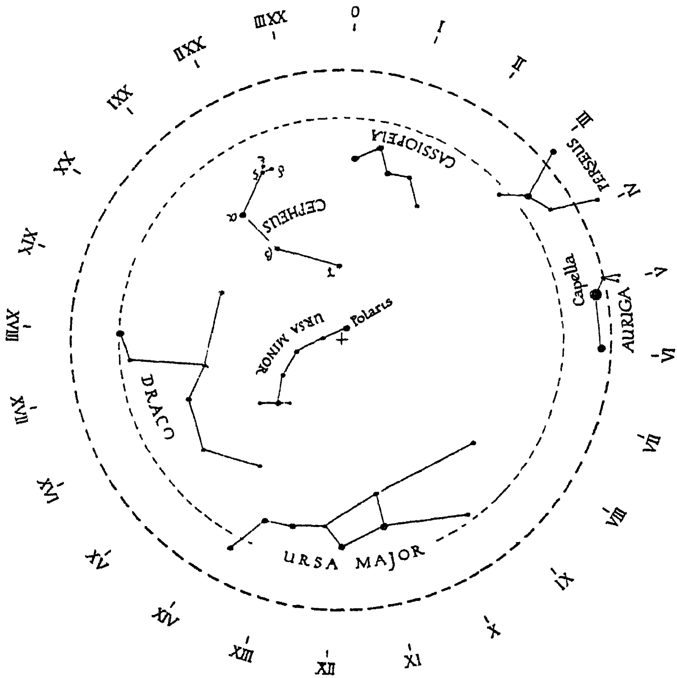


Fig. 2.—The circumpolar constellations

The polar stars appear to rotate about a fixed point, marked with a cross, called the pole, round which are drawn two circles. The inner circle marks the points in the heavens which are directly overhead at Greenwich during transit; stars within this circle pass between the zenith—the point directly overhead—and the pole,

whereas those outside it pass south of the zenith once in every twenty-four hours as the earth rotates. The outer circle is the horizon at lower transit, and all the stars within this circle never set at Greenwich; for example, Capella is always visible at Greenwich, and passes once directly underneath the pole (lower transit) and once overhead (upper transit)—just south of the zenith—in every twenty-four hours. One can always see a bright star like Capella from Greenwich with a telescope, unless it is cloudy or foggy; but one cannot see the stars with the naked eye in the daytime since they do not stand out enough from the blue sky. One can actually see the rotation of the polar stars if one stays up all night to watch for it, or rather, one can see just half of the complete rotation, the other half taking place in broad daylight. Few people will want to do this, but if you note carefully the position of the northern constellations on a clear night and look at them again after two or three hours have elapsed, you will find that they have all shifted round the pole a bit in the anticlockwise sense—the opposite sense to that in which the hands of the clock go round. Stars that you first saw directly beneath the pole have shifted to the right and up; those originally overhead have passed on towards the west. This apparent motion is linked up with the daily movement of the sun, and it arises because it is the earth under our feet which is turning round once a day; the stars stand still (very nearly), and the sun moves about among the stars but makes little progress in a day. The pole appears to stay still because it is in this direction that the earth's axis of rotation points.

It is easy enough to see where the moon is among the

stars, because moonlight is not so bright that it masks the star light; but it is considerably less easy to tell where, exactly, the sun is, because you cannot see stars with the naked eye in the daytime. The ancients used to watch very carefully to see what stars rose and set just before sunrise and just after sunset. It is important to know where the sun is, because the arrival of spring and summer depend on the northerly movement of the sun. It is not necessary for the private citizen to bother about this nowadays, because the calendar is carefully watched and kept adjusted by extra days in leap years so that the vernal equinox—the sun's passage over the equator from the southern sky to the northern sky—always comes in March. But in the earliest days of ancient civilizations it was not at all obvious when to expect the spring and when to sow the crops. In these days everybody knows that there are 365 days in an ordinary year, and 366 in a leap year. Which means that it takes nearly 365¼ days for the sun to get just once round the heavens, and give us the same season again. The adoption of a calendar which recognizes 365¼ days in the year is due to Julius Cæsar, who found that the calendar actually used when he came to power, which had been in use for some centuries, in which there were 355 days in the year plus days which the priests *intercalated*, had accumulated so much error that the spring no longer came in the month in which it was supposed to come, but came about two months late every year! After consulting the opinion of Sosigenes, Cæsar supposed that the year contained *exactly* 365¼ days, and invented the Julian system in which three years of 365 days each are followed by a leap year of 366 days. This

calendar was untouched until the seventeenth century. Now the actual length of the year is very nearly 365 days 5 hours 48 minutes and 48 seconds, so that the Julian calendar is in error by 11 minutes 12 seconds a year, or 0·778 days in a century. By about A.D. 1550, therefore, when the calendar had been used for 1600 years, it was in error by 10 days. The sun had got round the 1600 laps of its unending track a bit more speedily than Cæsar had anticipated, and instead of getting to the equinox on 21st March it was already there on 11th March. It was necessary to call the day which was 11th March on the Julian calendar "21st March" to put the matter right. The calendar was pushed on 10 days by Pope Gregory in 1582, and many ignorant people thought that they were being cheated of 10 days of their life.

The calendar was not changed from the Julian to the Gregorian system in Great Britain for a further two centuries—during which the Roman Catholic Easter was liable to differ from the British Easter. When at last the change was made (in 1752) it was denounced as Popish and impious. The day 3rd September, 1752, old style, was called 14th September in the new style, and there were only 19 days in that month of September. In the country districts of Lincolnshire new tenancies still begin on 6th April—which is Lady Day in the old Style—and annually engaged farm servants go for their holidays on "Pag Rag Day", 13th May—the morrow of the old May Day; even the British Government has never completed the change from the old to the new style, as the Income Tax year ends on 5th April, which is the *old* Lady Day!

We keep the Julian calendar a little more closely

in touch with the facts by counting only 365 days in those centurial years which are not divisible by 400, such as 1700, 1800, and 1900, but not 2000, so that the calendar equinox is now only in error by one day in four thousand years; and it can always be put right when astronomical observations of the equinox call for it by the addition or suppression of a leap year.

The spectacle of the heavens passes ceaselessly overhead; the days and nights alternate; the sun rises afresh every morning. Is it always the same sun? Primitive people sometimes thought that a new sun was created every day, if not, how did the sun get back from the west to the east, under ground, every night? Travel would have shown the ancients that the sun was always the same. One has only to go within the arctic circle in the summer, say to Tromsö in Norway, to see the sun above the horizon at midnight. In these northerly latitudes at midsummer the sun does not set at all. It goes round the pole—which is nearly overhead—in somewhat the same way as a circumpolar star like Capella does at Greenwich, with the difference that the arctic pole is more nearly overhead than the Greenwich pole, so that the sun sweeps round the horizon without rising much above it. It moves round from east in the morning through south at midday, west in the evening and due north, but unhidden at midnight.

In the days of Copernicus there was no reason to suppose that the earth rotated every day rather than that the sun went round the earth—except a general appeal to common sense, taking account of the fact that the sun is much larger than the earth—but in 1851 the great French physicist Foucault demonstrated

the earth's rotation in the following manner. A heavy iron ball was suspended from the dome of the Pantheon by a wire more than two hundred feet long. The ball was pulled aside and held still by a thread; when it had been left for some time at rest the thread was burned and the great pendulum started swinging in a plane. The plane in which the pendulum was swinging then appeared to swing round slowly in the direction of the hands of a clock, at the rate of about ten degrees an hour. In reality, the plane of the pendulum remains fixed, and the floor of the Pantheon was actually turning round under it. Such a pendulum hung at the North Pole of the earth would appear to turn its plane round just once in 24 hours of sidereal time; at the equator nothing at all would happen, and at intermediate points the rate at which the plane of the pendulum turns round depends on the latitude. A gyro compass gives exactly the same proof that the earth is in fact rotating once every sidereal 24 hours.

While there can be no doubt that the actual rotation of the earth accounts for the apparent diurnal motion of the heavens—the ordinary phenomena of rising and setting—it is not so easy to account for the annual motion of the sun through the constellations. It was usual in the middle ages to suppose that the sun actually described a circular path round the earth every year and it was a revolutionary suggestion, proposed by Copernicus, to regard the sun as a fixed body and to suppose that the earth travels once a year round the sun. The appearance of the heavens and the apparent annual motion of the sun through the heavens would be the same in either case. If the sun actually described a circular path about the earth, the stars being fixed,

we should see just what we do see; an annual motion of the sun through the stars. Copernicus realized that we should see exactly the same thing, an apparent annual motion of the sun through the stars, if the sun were fixed and the earth rotated about the sun. The adoption of Copernicus's broadminded view that we should consider not our petty planet but the massive sun as the centre of things was rewarded by the discovery in later years of the dynamical laws which govern the earth's motion about the sun.

Why does the sun appear to move northwards in the spring and southwards in the summer? This is not a sensible question; we see that it does, and we are led to the purely descriptive statement that the equator does not coincide with the ecliptic; the earth's axis of rotation does not happen to be perpendicular to the plane in which the earth moves round the sun.

So far we have said nothing about the length of the day, and its subdivision into hours and minutes. It was not really practicable to define the day and the hour exactly until pendulum clocks were invented. If you hang a heavy weight by a long string, and set the weight moving you will find that the time the weight takes to swing backwards and forwards is always the same, whether the swing is a big one or small one. *You* can test the truth of this statement with a stop watch, or with the seconds hand of an ordinary watch; but the first person to notice it was Galileo Galilei who had no watch, as he lived before the days of accurate clocks. Galileo thought that the time of swing of a great pendant candelabra in the cathedral at Pisa was the same whether the candelabra was executing great or small swings, and he had to test

the truth of his idea by comparing the time of swing with the beat of his own pulse. This principle is the basis of the pendulum clock, the grandfather clock, and the beginning of the accurate subdivision of the day into twenty-four hours. A clock simply is a pendulum swinging regularly backwards and forwards, with devices for keeping the motion going (against friction) and for counting the number of swings.

Once the accurate clock had been made it became possible to fix the length of one day. The lapse of time from sunrise to sunset will not serve the purpose because this varies from summer to winter; we want for the day as a standard of time something that will not vary at all. If you set up a vertical wall running true north and south, that is to say, such that when you look along the surface of the wall you see the pole of the heavens, and then observe with your clock the number of beats which elapse between successive passages of a star past the plane of the wall, you will find that these intervals are all the same length. Every star passes the wall once every *sidereal day*, which is divided into twenty-four sidereal hours each of sixty sidereal minutes. The early astonomers had an actual wall, but now the wall is replaced by a plane passing through the pole, and the place of observation, and containing the vertical line (the direction in which a plumb line will hang). This plane is called *the meridian plane*. The regularity with which the stars pass through the meridian plane is the regularity with which the earth turns on its axis; and it is very, very regular, much more so than the best clocks that have ever been constructed, and though it is not impossible that mankind should some day

construct a clock that will keep better time than the earth itself does, this super clock of the future will have to gain or lose less than one-tenth of a second in a year if it is to compete with the earth. So much for sidereal time. But what about the sun? Regarding for the moment the spinning earth as the centre of the universe, the sun goes round it once a year, the stars being fixed, and the sun appears to make one fewer revolution in a year than the stars do.

Observations show that the sun gets back to the same place among the stars after the lapse of 366·2422 sidereal days, so that the year which is 366·2422 sidereal days is 366·2422—1 or 365·2422 solar days. This defines the mean solar day, which is subdivided in the familiar way into 24 hours, 1440 minutes and 86,400 mean solar seconds. But when we examine the successive transits of the sun past our wall (through the meridian plane) they are not exactly 86,400 mean solar seconds apart. The sun is sometimes late compared with the stars and sometimes early. The difference between mean noon and the actual instant when the sun crosses the meridian is called the equation of time; it amounts to as much as 16 minutes in the beginning of November. Midday is not always the instant when the sun is due south, and a simple sundial does not give the correct civil time until the equation of time is applied. The stars are our true timekeepers.

This irregular behaviour of the sun is partly a consequence of the fact that the equator is inclined to the ecliptic. If the sun travelled at a constant angular velocity round the ecliptic it would not cross the meridian at equal intervals of time; at the equinoxes part of its velocity is used up in getting from north to south

or south to north. But the sun does not even go round the ecliptic with constant velocity. As the earth's orbit is not circular but slightly elliptical, the earth does not go round the sun with a uniform velocity, so that the apparent solar motion among the fixed stars is not uniform, being a reflection of the earth's motion round the sun.

Astronomers imagine the skies to be divided up in the same way as the terrestrial globe is divided by parallels of latitude and meridians of longitude. The astronomical latitude is called Declination, and it corresponds closely to terrestrial latitude, being 90° at the pole and 0° at the equator. When you divide up the globe into meridians of longitude you must choose arbitrarily some place at which to begin—the meridian of Greenwich is now universally chosen. Some conventional counterpart to Greenwich has to be chosen in the heavens, and the vernal equinox is taken for this purpose. Astronomical longitude is called Right Ascension, and instead of being measured in degrees like terrestrial longitude, it is given in hours and minutes, the twenty-four hours of the sidereal day being spread out round the sky. The Right Ascension of a star is one hour if it crosses the meridian one hour after the vernal equinox has crossed it. For example the right ascension of Capella is 5 hours 11 minutes, because Capella crosses the meridian 5 hours 11 minutes in sidereal time after the vernal equinox has crossed. The beginning of the sidereal time is the transit of the vernal equinox, so that the sidereal time of the upper transit of Capella is $5^{h.}\ 11^{m}$; more generally, the sidereal time of the upper transit of any star is simply its right ascension. The hours of sidereal

time are marked in Roman numerals round the circumference of the diagram of circumpolar stars on p. 7. The work of finding out the right ascensions of the bright stars has been completed by the great observatories (though the values have to be revised from time to time) and the right ascensions of the stars are printed in the Nautical Almanac. From the tables of the stars' right ascensions, one can always tell the *sidereal time*, which is simply the right ascension of the star which is crossing the meridian at the moment. Of course there is not always a convenient bright star about to cross the meridian, but the astronomer corrects his clock showing sidereal time by noting its reading when a bright star does cross the meridian; the clock should show $5^{h.}\ 11^{m.}$ when Capella crosses the meridian on its upper transit, and so on. One can make a rough observatory for sidereal time out of a high building if its wall is straight and vertical. Stand south of the edge of a wall in such a position that Polaris appears just to touch the edge of the wall. The observer's eye is then approximately due south of the edge, and the plane containing the edge and the observer's eye is the meridian plane. One can then watch the bright circumpolar stars appearing from behind the wall or disappearing behind it. If the wall is on the east side of the building the stars will disappear on their upper transit and appear again twelve sidereal hours later. The sidereal time is equal to the right ascension of the star which disappears on its upper transit, and is twelve hours ahead of the right ascension of the star appearing on lower transit.

The sidereal time is nearly the same as the ordinary civil time on 21st September, except that in civil

time we adhere to an ancient custom of splitting up the twenty-four hours of the day into two sets of twelve hours each and calling the hours from 13 to 23 "1 to 11 p.m.".* On 21st March the sidereal time differs from the civil time by twelve hours. Since there are 366¼ sidereal days and 365¼ civil days in the year, the sidereal day is about four minutes shorter than the civil day, and so the two times, which are together in September, soon get out of step. The sidereal time is 6 hours ahead of solar time on 21st December, 12 hours ahead on 21st March, and 18 hours ahead (or 6 hours behind) on 21st June. One can turn one into the other simply by consulting tables published in the Nautical Almanac.

The accurate observation of time as practised in a modern observatory is performed with an instrument called a Transit Telescope. The transit is essentially a telescope mounted on an axis at right angles to the direction of sight through the telescope (the optical axis of the telescope). The telescope is mounted so that it can turn in any direction north or south in the meridian plane by swinging it round on its axis; the bearings (A and B in the diagram) must be level with one another and due east-and-west. The observer then watches for the transits of a number of stars and corrects his sidereal clock, so that the time of transit of the star shown by the clock is equal to the star's right ascension. The exact time of transit is found by placing a fine mark—a spider's web—

* *Summer time* is the practice of falsifying the civil time by one hour during the summer months, in order to persuade citizens to rise from their beds and conduct their business in time to have an extra hour of daylight afterwards. The necessity for resorting to this peculiar device is a sad commentary on the folly of human habit.

just in front of the eyepiece of the telescope, and the time of transit is the time at which the star appears to cross the spider's web in the eye-piece of the telescope. Special precautions have to be taken

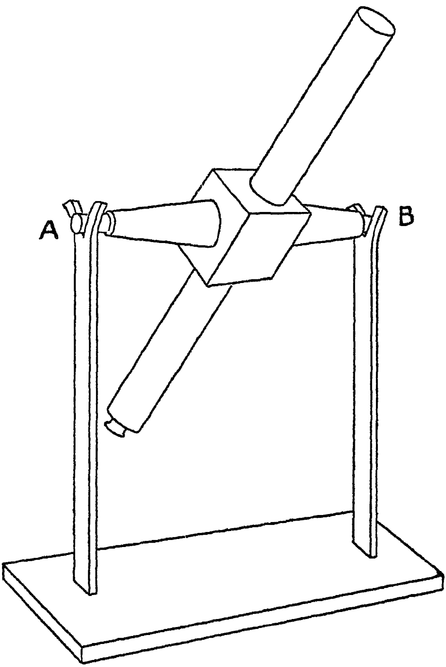


Fig. 3.—Transit Telescope

to ensure that the plane in which the telescope swings is really the meridian plane, and that the spider's web has been put in the right place in relation to the object glass (the lens in front of the telescope). In practice it is not necessary to make these adjustments quite accurate; instead, the observer finds out just how much they are in error and makes a small cor-

rection to the observed time of transit of the star.

The transit telescope is tested to see that its axis is level, by placing a spirit level across the bearings. When this is properly adjusted the instrument will point at the zenith when it is pushed into the vertical position. There remains the problem of adjusting the instrument's bearings east and west so that it will point at the pole. This is tested by observing successive upper and lower transits of a circumpolar star, say Capella. If the adjustment is perfect the upper and lower transits are exactly twelve sidereal hours apart, and the lower transit is exactly half-way in time between two successive upper transits. If the instrument is not set up properly, so that, say, it points a little north-east and south-west, the upper transits will appear a little too early and the lower transit a little too late, so that the lower transit will occur shortly after the half-way time between successive upper transits. "And for the more declaracioun, lo here thy figure." (Fig. 4.)

About a century ago the only method of estimating the time at which a star crossed a spider's web in the eyepiece of the telescope was the "eye and ear" method. The observer listened to the ticking of a seconds-clock and watched for the phenomenon, making an estimate of the time at which the transit occurred as best he might. When electricity came into general use in the middle of the nineteenth century, the "galvanic" method of recording transits was invented. The observer no longer listened to the beating of his clock, but pressed a button at the instant of transit—as well as he could estimate it. When he pressed the button he completed an electric circuit and sent a

E 946

THE MOON

From a photograph taken at the Royal Observatory, Greenwich

Facing p 20

current through an electromagnet which moved a fountain pen which was making a trace on a piece of paper wrapped round a drum. The clock beats closed the same electric circuit, so that the pen ticked every

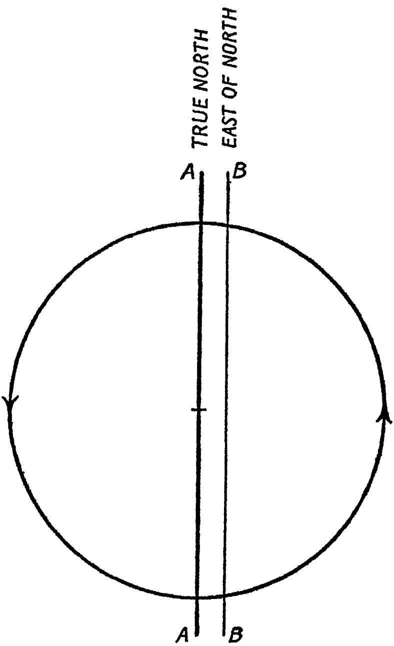


Fig. 4.—Azimuth of transit circle. If the instrument is correctly adjusted to swing in the plane of the meridian *AA*, the intervals between successive upper and lower transits will be equal; but if the instrument points east of north, *BB*, the interval between upper and lower transits is longer than the interval between lower and upper transit.

second. After the observation had been made the observer examined the paper and found his transit " tap " among the clock taps, and read off the distance from the next preceding clock tap. This distance is proportional to the time that has elapsed since the last

second beat if the drum is going round steadily. The galvanic method was an immense improvement over the eye and ear method. Two observers using the eye and ear method might easily disagree as to the time of a transit by as much as a second; using the galvanic method it would be unusual for them to disagree by as much as a fifth of a second.

One of the eighteenth-century Astronomers Royal, Maskelyne, discovered to his dismay that his assistant estimated times of transit consistently a second later than he did himself. Maskelyne assumed that an Astronomer Royal could not very well be in error in such a matter, and dismissed the luckless assistant. Some forty years later the great Bessel discovered a difference of a second between himself and the astronomer Argelander, and came to the conclusion that every observer has a "personality", and observes, quite consistently, always a little early, or always a little late. A difference of one second between two personalities was rather extreme even with the old eye and ear method. The personalities went on, on a much reduced scale, in the galvanic method. They have been still further reduced by the introduction of the "impersonal" method, in which the observer drives a moving wire in the telescope to keep pace with the star. The contacts are made automatically as the wire goes along, and the observer is no longer called upon to decide when the transit occurs. Personality still persists; some observers drive the wire a little ahead of the star and some a little behind; but a personality of two hundredths of a second would be considered quite large with the new method. It was customary, before the introduction of the impersonal method, to

suppose that some particular observer was the standard observer, and correct all the other members of the observatory staff for their personalities, to make them agree with the standard observer. This was done at Greenwich. When the impersonal method was adopted it was found that the standard observer himself had a personality of a quarter of a second, so that when the new method was brought in Greenwich time was actually changed by this amount. Few people, if any, noticed the change!

The determination of time has always been of great importance in the art of navigation. The fundamental problem is to determine, from astronomical observations alone, the ship's position, when out of sight of land. The surface of the globe is conceived to be divided by parallels of latitude and meridians of longitude. The latitude of any place is the elevation of the heavenly pole above the horizon at that place. Longitude can only be defined with reference to a fixed point on the globe; it is usual to define longitude as position east or west of Greenwich. The longitude of a place is the angle between the meridian plane at that place and the meridian plane at Greenwich. Latitude never presented much difficulty to the navigator; he can measure the elevation of the pole above the horizon, either by measuring the altitude of Polaris and applying a correction since the actual star is not exactly situated at the pole, or by measuring the altitude of *any* star whose declination is known at the time of its upper or lower transit. The figure shows that if λ is the latitude of the place and δ the declination of the star (both positive if northerly) then h, the altitude of the star at upper transit is $90° + \delta - \lambda$, so that if

the navigator measures h, he can find λ from $\lambda = 90° + \delta - h$.

The determination of longitude is much more difficult. The sidereal time at any place can be determined from transit observations. Now the earth turns round

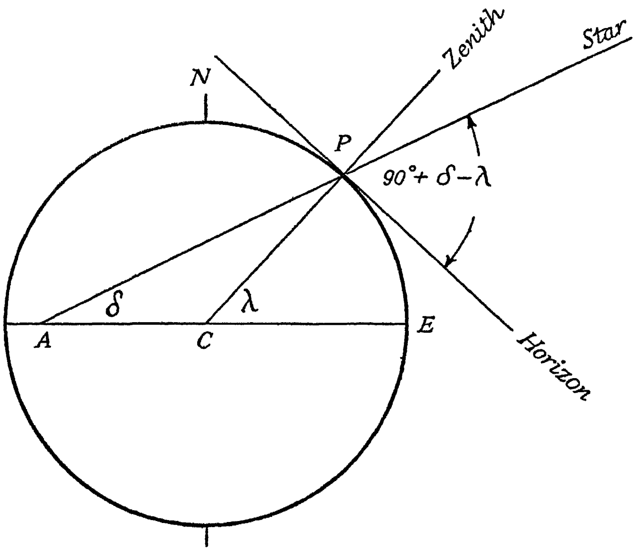


Fig. 5.—Determination of latitude from the elevation of a star at culmination. *C* is the centre of the earth, *E* is on the equator and *N* is the earth's north pole. The star's declination δ is the angle *PAE*, and the latitude λ of the station *P* is *PCE*. The altitude *h* is the elevation of the star above the horizon and is equal to $90° + \delta - \lambda$.

through one revolution, or 360°, in 24 hours, so that it turns through 15° every hour. If you were looking down at the earth from Capella you would see a certain meridian of longitude facing you; let us suppose it is that of Greenwich. To observers on this meridian it would appear that Capella was in transit on their meridian plane at this time. Looking down from Capella

an hour later, you would see that the earth had turned through 15° and that the meridian 15° W. of Greenwich was now facing you, and observers who were 15° W. of Greenwich would record the upper transit of Capella. In both cases they would say that the sidereal time is 5 hours 11 minutes, and one says this an hour later than the other; so that the sidereal time is not the same in different longitudes. On the meridian 15° W. of Greenwich the sidereal time is 1 hour behind Greenwich sidereal time; at 30° W. of Greenwich it is 2 hours behind Greenwich sidereal time; and so on. The navigator takes with him a chronometer which keeps Greenwich time—sidereal or solar, it does not matter which. Then he observes the local time by astronomical observation, and the difference between local time and Greenwich time tells him his longitude. If the local time is 1 hour behind Greenwich time he is 15° W. of Greenwich, and so on. Before the invention of the chronometer it was very difficult to find out the Greenwich time when you were not at Greenwich itself; the grandfather clock could not be carted about, and would not go at all on a ship rolling in a heavy sea. It was the practice of navigators trying to make the Cape of Good Hope in the early eighteenth century to sail deliberately too far west until they had got to the right southerly latitude, when they would sail eastwards, keeping to this latitude until they sighted land. It was generally felt that it was urgently desirable to invent a method of finding the longitude at sea. Charles II took a personal interest in the problem, and founded the Royal Observatory at Greenwich with the object of observing the motion of the moon among the stars with such precision that the Greenwich time could

be found by the moon's position, but the work was more laborious than was at first realized. In 1713 the British Government offered a reward of £20,000—a large sum in those days—to the first inventor who should perfect a clock which would go to sea and keep accurate time. The reward was not won until 1764, when Harrison made a watch-chronometer which fulfilled the stipulated condition of making a voyage to Jamaica and back without gaining or losing more than one minute of time. Harrison's chronometer is still kept at the Royal Observatory at Greenwich, together with a copy of it which was used by Captain Cook on his voyage to New Zealand. Navigation continued to depend on the accuracy of the chronometer until recent times when the perfection of wireless telegraphy has enabled us to signal Greenwich Mean Time all over the world. This is done twice a day from the station G.B.R. at Rugby, and the "six pips" for the use of private citizens in Great Britain is familiar to everybody.

It is not possible to erect a transit instrument at sea, as the vessel is never steady enough to permit of the fixing of the instrument in the meridian. The navigator has to work on a different plan, and measures the altitudes of the sun and stars above the horizon with a small instrument called a sextant, which measures the angle between one thing and another, and it is used to measure the elevation of the sun, or of a star, above the horizon. A star of a given right ascension and declination reaches a given elevation at a certain sidereal time which can be calculated: for example, in a given latitude the local sidereal time is such and such when Aldebaran has risen so many degrees above the horizon.

The navigator subtracts this from the Greenwich sidereal time shown by his chronometer when Aldebaran is observed to reach this elevation, the difference giving him his longitude east or west of Greenwich according to whether the local sidereal time is greater or less than the Greenwich sidereal time. No single observa-

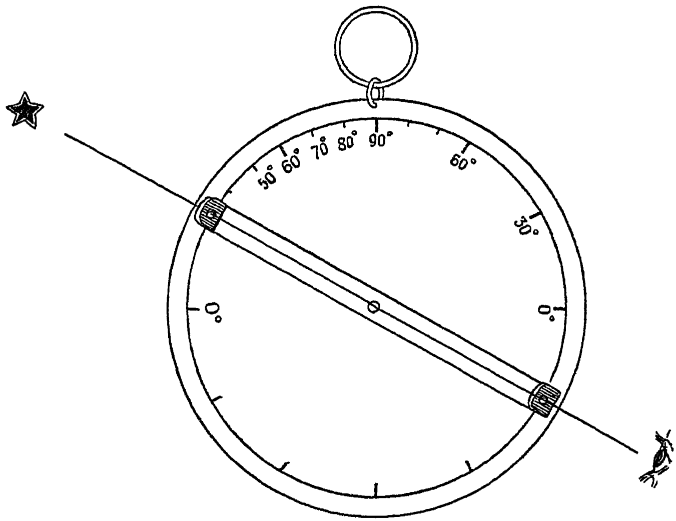


Fig 6 —The astrolabe

tion will determine both latitude and longitude, and when it is required to determine both these quantities at sea the navigator has to make at least two observations, preferably of the altitudes of two stars.

Before the invention of the sextant elevations were measured with an instrument called an astrolabe. This consisted of a sighting arm provided with two end pieces in which holes were pierced. The arm was bolted to the centre of a plate the circumference of

which was engraved with degrees, like a protractor. The whole instrument was suspended from a ring passing through the mark 90°, through which the observer passed his thumb, and adjusted the rule until he could see the star through the sighting holes. The elevation of the star was then read off directly on the protractor scale. The poet Chaucer, who had a deep interest in astronomy, wrote a treatise on the astrolabe in which he explained the construction of the instrument and also how to use the observed elevation of the sun, or of a star, to determine the time; in the form in which Chaucer describes it the astrolabe is a combination of the simple instrument for determining elevations with a mechanical device for converting sidereal time into solar time.

Before the invention of wireless telegraphy the moon afforded one of the best methods of determining longitude. The moon goes round the heavens once a month. If you notice the moon's position among the stars on one night and observe it again on the following night you will find that it has moved through about one hour of right ascension. (It rises roughly an hour later every night.) One hour of right ascension being 15° of arc, the moon moves through nearly half a degree every hour, or one minute of arc every two minutes. Its movement through the stars is very regular, and it is possible to draw up tables showing in advance what the moon's right ascension will be hour by hour for years in advance. The moon is, in fact, like the hand of a great clock passing once a month round the sky, and the tables are drawn up in such a way that they show the Greenwich sidereal time at which the moon occupies each position in right ascen-

sion. The navigator who doubts whether his chronometer is still keeping good Greenwich time tests the matter by observing the moon's distance from neighbouring stars and calculating the moon's right ascension. He then looks in the Nautical Almanac to find out what was the Greenwich time when the moon had this particular right ascension, and compares this with the time indicated by his chronometer. He finds out in this way whether his chronometer is fast or slow on true Greenwich time, and keeps this correction for future use in finding his ship's longitude. But in these days it is much easier, as well as much more accurate, to correct the ship's chronometer by the wireless signals.

CHAPTER II

The Solar System

AFTER the sun, the most conspicuous body in the heavens is the moon, the most obvious features of which are its phases. These arise because the moon is not a self-luminous body, and we only see it by reflected sunlight. The moon goes round the earth once a month of 28 days in the same sense as the earth rotates, so that it rises later by approximately one-twenty-eighth of a day—just less than an hour—every night. When the moon rises at sunrise it is between the earth and the sun; consequently, the illuminated side of the moon is turned away from us and we see nothing; this is the new moon. A few days later we begin to see a thin crescent of the illuminated half of the moon. A fortnight after new moon the moon has got right round so that it is on the opposite side of the earth to the sun, and rises at sunset. We then see all of the illuminated half of the moon, and the moon is said to be full. At intermediate times between new moon and full moon we see more or less of the illuminated portion according to the position of the moon on its way round the orbit. Under exceptional circumstances one can see the dark part of the moon shining by sunlight reflected on to the moon from the earth; this is called " the old moon in the new moon's

arms ". It is only seen, in the evenings, just after new moon. The reader may have noticed that the full moon never rises very high above the horizon in the summer, while the new moon is very far north at this time of the year, the position being reversed in the winter, when the full moon is very high in the heavens at midnight, and the new moon is far south. This state of affairs has a simple explanation. The moon is never very far from the ecliptic, the inclination of the moon's orbit being 5° 8′. Now the earth's pole is inclined to the pole of the ecliptic, and in summer the pole is turned towards that direction in which the sun lies, so that that part of the ecliptic in which the sun is situated is elevated north of the equator. The other half of the ecliptic is correspondingly depressed to the south of the equator. As the moon goes round its orbit, approximately coinciding with the ecliptic, it reaches the elevated side of its track when it is on the same side of the earth as the sun, that is to say, at and near new moon, so that the moon is north of the equator and high in the heavens at this time; and when the moon is full it is on the depressed side of the ecliptic, and well south of the equator, so that it is not very high above the horizon even at its upper transit. A similar argument accounts for the high full moon and low new moon in the winter. This explanation is given for an observer in the northern hemisphere, but *mutatis mutandis* it applies equally well to an observer in the southern hemisphere. The moon is a striking object when viewed through even a modest telescope. The best idea of its appearance is given by a photograph, such as that on Plate II. The mountains and craters are most con-

spicuous near the edge between the bright and dark halves of the surface; at these points the sunlight grazes the moon and the mountains cast deep shadows, like mountains on the earth at sunset. There is no atmosphere on the moon; we know this from the lack of haze, the clearness with which the lunar mountains cast shadows and the lack of any refraction effects when the moon passes a star. Since at every new moon the moon comes between the sun and the earth in right ascension, we should find that if the moon's orbit

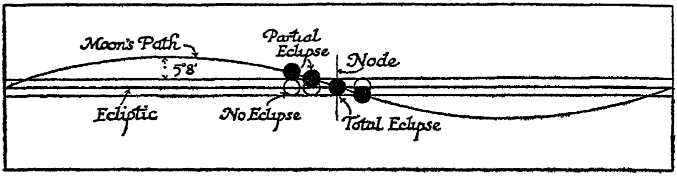


Fig. 7

was in the ecliptic, at every new moon the moon would appear to pass over the sun's disc; but on account of the inclination of the moon's orbit to the ecliptic the moon passes over the sun or under the sun in most cases. The inclination of the moon's orbit is variable, but the mean value is 5° 8′. (The greatest *declination* of 28° is made up of two parts—the inclination to the ecliptic, and the inclination of the ecliptic itself, which is 23°.)

The moon's apparent orbit is shown in the diagram (fig. 7); the places where the moon crosses the ecliptic are called *nodes*. Unless the moon is near the node at the time when it is also between us and the sun (i.e. at new moon) it will pass over or under the sun and miss it entirely; but when the new moon

occurs at a node of the moon's orbit it will cover up at least a part of the sun's disc. This phenomenon is called an eclipse of the sun. Since the moon and sun appear to be almost exactly the same size, it is difficult to get an exact fit of the moon over the sun—a *total* eclipse of the sun. When the fit appears exact from one point on the earth's surface it does not, in general, appear exact from another point a few miles away. A total eclipse at a particular spot is a very rare occurrence. There was a total eclipse in England in 1927, but another will not occur until 1999, when there will be a total eclipse visible in Cornwall. There will be many total eclipses in various parts of the globe before that; in 1936 there was a total eclipse whose path swept from Constantinople over Siberia to Japan, and in 1940 there will be a very fine total eclipse visible in Brazil and South Africa.

The prediction of eclipses is simply the prediction of the coincidence of the moon passing through its node and the new moon. The ancient Chaldeans noticed that these coincidences occur at a regular interval of 18 years 11⅓ days. They named this period the *Saros*.

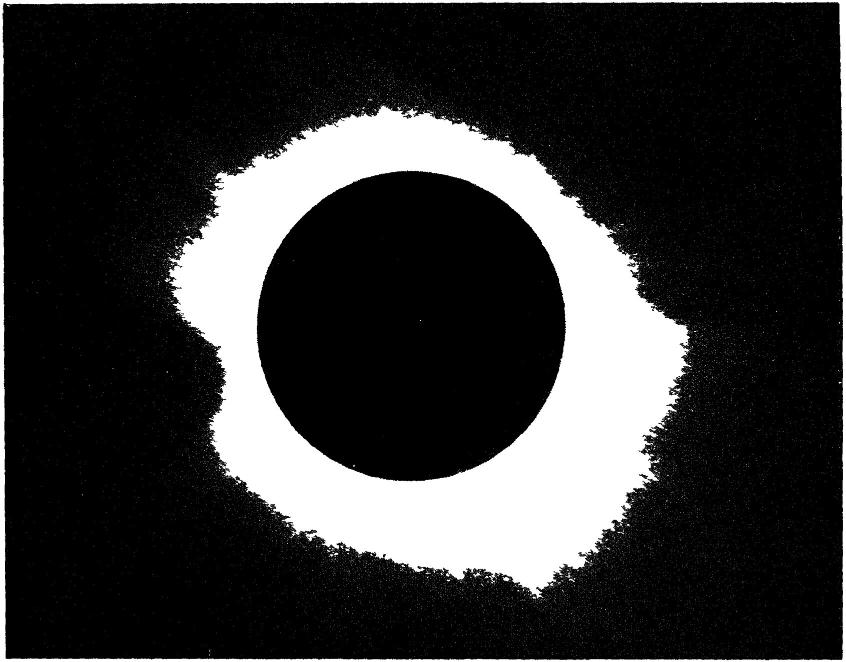
The appearance of a total eclipse of the sun is very striking. When the moon exactly covers the sun's disc one can see the solar corona and the solar prominences which cannot be seen at ordinary times because of the powerful glare of the sun. The prominences are great jets of gas which project beyond the limb; they may be as much as 400,000 miles high; and the corona is a very large tenuous halo which envelops the sun at all times, though its form changes from time to time, and it appears quite different from one eclipse to another.

Eclipses of the moon occur when the earth passes directly between the sun and the moon, casting a shadow on the latter. These occur when the moon passes through a node at *full* moon. They are of considerably less interest than eclipses of the sun.

The moon describes her orbit under the influence of the earth's gravitational pull—the same force which attracts heavy objects to the earth's surface. The moon exerts an equal and opposite force on the earth. This force is slightly stronger on that side of the earth which faces the moon than on the other side, and this difference in the moon's pull has two effects; firstly, the ocean tides, and secondly, the precession of the equinoxes.

In describing the elementary facts about the daily and annual motions of the celestial objects, it is convenient to speak as if the equinox was a fixed point; but in fact the equinox drifts westwards very slowly. The rate is such that the equinox travels once round the ecliptic in 26,000 years, the westward movement being 50 seconds of arc per annum. This movement of the equinoxes was discovered by Hipparchus (125 B.C.), who found that the year from midsummer to midsummer, which he measured by the least shadow cast by the sun, was twenty minutes of time shorter than the year judged by the sun's return to the same constellation. The movement is called the *precession* of the equinoxes. The pull of the moon on the earth, which is not quite spherical, tends to pull the equator into the plane of the moon's orbit, but since the earth is spinning, the attempt is unsuccessful, and results in the slow precession of the pole of the earth's rotation. One may see the same phenomenon in a

N



W

E

A TOTAL ECLIPSE
OF THE SUN

From a photograph taken at Sobral, Brazil, May 29, 1919, showing the corona (the halo round the sun) and a very large prominence in the S E quarter

E 846

Facing p 34

child's top, spinning rapidly; when the top is not vertical the force of gravity which would make a non-spinning top fall over makes the top's axis precess; while the top spins, its axis moves slowly round the vertical, keeping at a constant angle to it. The earth's pole, then, precesses about the pole of the moon's orbit. A result of this motion is that the present pole star is only a temporary occupant of that office; in A.D. 14,800 the pole star will be Vega. Besides the gross motion of precession the earth's axis executes a much smaller movement called nutation, a nodding of the axis. This is also caused by lunar attraction.

Besides the sun and the moon there are a number of bodies which wander among the fixed stars: these wanderers are called planets. Their motions were observed assiduously by the ancients, who associated various deities with them; the names of these deities—Mercury, Venus, Mars, Jupiter and Saturn—have remained with the planets to this day. Each planet received a name suggested by its appearance; for example, the red colour of Mars suggested the god of war. Unfortunately, the ancients were only too ready to confuse fancy with fact, and supposed that the planets must exert influences over the destinies of men corresponding with the powers popularly attributed to the gods with which fancy had identified them. The configuration of the planets at any time was held to influence an event, such as a battle; but the mystic influence on a man's destinies was most intense at the times of his nativity. This superstitious folly, which went under the name of astrology, persisted well into the middle ages. It is a curious fact that there are still plenty of credulous people who like to believe in it,

although it is not so hard to understand that there are persons willing to profess astrology—for suitable fees.

It was at first supposed that the sun described a circular path round the earth—which was the firmament, the centre of the universe—and that the planets described circular paths round the sun. Copernicus (1473–1543) made a great advance over the thinkers who preceded him when he supposed that the sun was fixed, and that all the planets, including the earth as one of a family, described circular orbits round it. But the true laws of planetary motion were discovered by Kepler after the astronomer Tycho Brahe (1546–1601) had spent a lifetime in conducting measurements of the relative positions of the sun and the planets. Tycho's observations were worked up by Kepler (1571–1630), who was Tycho's pupil and who found out the following laws of planetary motion:

1. The planets move in elliptical orbits in which the sun is in one focus.

2. The rate at which the line joining a planet to the sun sweeps out area is constant.

3. The cubes of the times which it takes the planets to get once round their orbits are proportional to the squares of the semi-major axes of the orbits.

I have given the rules in their full mathematical glory; for which I apologize to the non-mathematical reader, to whom I must now address a word of explanation. The ellipses are not quite circles; for descriptive purposes they are *slightly elongated circles*. The ellipse is not a notion clearly recognized in everyday speech like the circle, but roughly corresponds to what is called *an oval* in ordinary language. (We do not use the word "oval" in mathematics, because

"oval" is a looser term; not all ovals are strictly elliptical.) An ellipse can be drawn with the help of two drawing-pins and a piece of string. Tie the ends of the string together to form a continuous string round the pins, and slip the point of a pencil inside the string so as to keep it taut. Now move the pencil round the pins, keeping the string taut. The pencil describes an

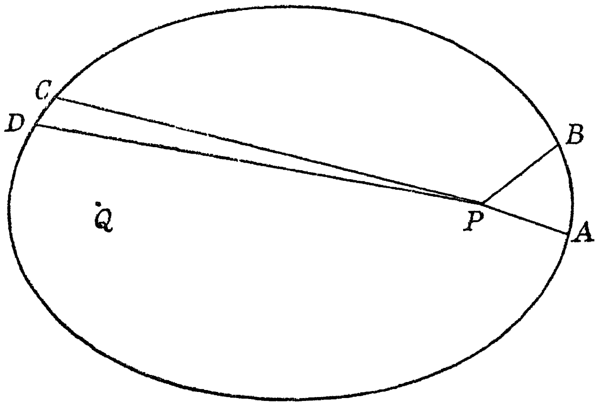


Fig. 8.—The figure shows an ellipse of which *P* and *Q* are the foci. The law of areas of planetary motion tells us that a planet, describing this orbit with the sun at focus *P*, would take as long to get from *C* to *D* as it takes to get from *A* to *B*, the areas *CPD*, *APB* being equal.

ellipse, of which the foci are at the pin points. By moving the pins closer together or farther apart one can get all kinds of ellipses, ranging from nearly circular ellipses when the pins are close together to elongated ellipses when they are far apart.

Rule 2 would mean that the planets went round uniformly if their orbits were circular; as it is they move more slowly when they are in that part of their oval which is farthest from the sun, and more rapidly when they are nearer the parent body (fig. 8).

Rule 3 means that the bigger the orbit the longer it takes to describe it; it follows from this rule that if you know the size and the period of any one orbit, you can calculate the sizes of the other orbits from the observed periods. The periods can all be observed directly, each period being simply the time it takes the planet to make one revolution round the sun; if we know one radius we can calculate all the others from it.

The planets describe orbits round the sun because they are attracted towards it. One can illustrate the principle involved by tying a stone to a piece of string and whirling it about one's head. The stone describes, roughly, a circular path, into which it is forced by tension in the string. If the string breaks the stone will fly off into the distance. Similarly, some force must be at work which attracts the planets to the sun. This fact was generally recognized towards the close of the seventeenth century. Tycho Brahe and Kepler who established the elliptical motion of the planets were unable to account for the dynamics of the motion; indeed, neither appears to have taken an interest in dynamics. It occurred to Isaac Newton, as perhaps it occurred to many others in his time, that *gravitation* might be the force which controls planetary motion. Newton (1642–1727) was born into an age familiar with the Copernican system, and more or less familiar with the elements of mechanics as investigated by Galileo. From time to time discussions arise about the extent to which Galileo anticipated Newton's laws of motion, and the extent to which others among Newton's contemporaries anticipated his universal law of gravitation, but it is one thing to speculate what may be the truth, and quite another thing to prove the truth

of it. Newton proved that the same force which made the apple fall was the force which held the moon in its orbit round the earth, and that the elliptical motion of the planets was due to the gravitational pull of the sun. Newton had to invent the differential calculus in order to prove his points and his achievement was truly great. He gathered together the work of the preceding century and welded it into a single, compact theory of dynamics in general and of the dynamics of the planetary motions in particular. The fact that his predecessors and contemporaries had seen the nature of the planetary problem and had even—like Halley—attempted to solve it, in no way detracts from Newton's achievements but rather heightens their greatness.

The distances of the moon and of the planets from the earth can be measured by an application of the principle which underlies the range-finder used in gunnery. It is a very important principle in the investigation of the heavens and we must go into it thoroughly.

Suppose that it is required to find the distance of the point C from the observer, stationed at P (fig. 9). The observer has with him an arrangement for measuring angles and a yard stick AB. He measures the two angles CAB and CBA. The farther off the point C is, the more nearly do these angles become right angles, and if the object is very far off he will not be able to distinguish between the angles that he actually measures and actual right angles. Now the sum of the three angles in a triangle is equal to two right angles, according to Euclid; so that by subtracting $\angle$CAB plus $\angle$CBA from two right angles the observer measures the angle ACB, which is called *the parallax*

of the object at C. The smaller the parallax, the farther off is the object. When the parallax is known it is possible to calculate the distance PC from the length of the yardstick AB.

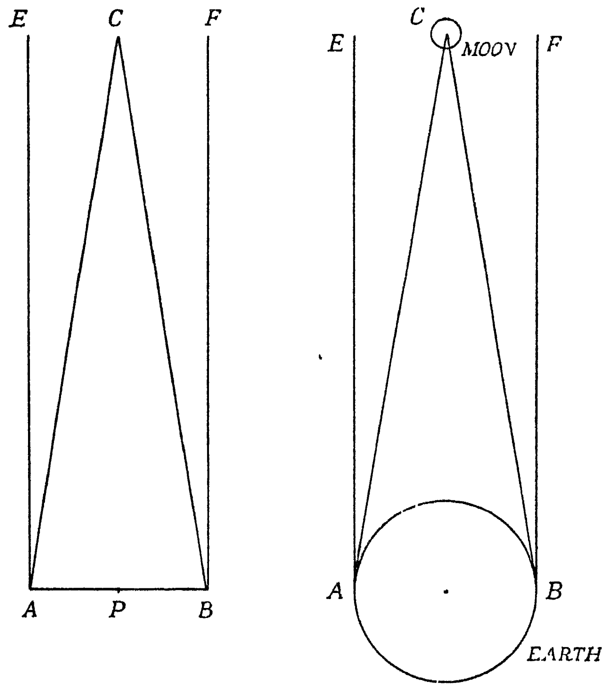


Fig 9—Measurement of distance

In order to get a parallax which is large enough to measure, the yardstick AB must be comparable with the distance PC. Where, then, shall we find a yardstick big enough to measure the distance of the moon from the earth? The answer is that the earth itself must serve as a yardstick. The diameter of the earth,

which can be found from terrestrial measurements, is quite a big enough base.

Suppose that the points A and B are at opposite ends of the earth. The lunar parallax can be found by measuring the angles EAC and CBF (since you cannot see B from A it is no use trying to measure the angles CAB and ABC as in the terrestrial range-finder), provided that AE is parallel to BF. In practice it is sufficient to take for AE and BF the lines joining A and B to a very distant star; these rays will be sufficiently nearly parallel for the purpose in hand. The observer at A finds a certain mark on the moon's disc about one degree west of the direction AE—marked by a certain star—and the observer at B finds that it is about one degree east of the same star. Comparing notes they deduce that the lunar parallax is about two degrees. Since the moon's orbit is not exactly circular the lunar parallax is not always quite the same; it varies from about $1° 48'$ to $2° 2'$. It is not necessary to send a colleague to Japan in order to determine the lunar parallax; only stay still and in twelve hours time you will get there yourself! On account of the earth's rotation you will have been transported to the side of the earth in space which was occupied by the Pacific Ocean twelve hours earlier. The measurement of lunar parallax is conducted by observing the moon's position among the stars in the evening, and then measuring it again in the early morning. The moon will appear to have moved. Part of this movement is the moon's monthly journey round the earth; subtract this and you are left with the parallax.

Now the earth's equatorial diameter is 7927 miles.

If you draw an isosceles triangle ABC in which AC = BC and the angle at C is 1° 55′, you will find that the ratio of the height CP to the base AB is 30·13 : 1, so that the mean distance of the moon from the earth is 30·13 times the earth's equatorial diameter or 238,900 miles. This is a great distance, but it is a mere bagatelle in comparison with the distance of the sun from the earth; and this in its turn is as nothing in comparison with the distance from the earth to the nearest star.

The solar parallax might be determined in the same way, but as it is only 17·6 seconds of arc (the angle subtended by an object six inches long when a mile away from the observer) it is more accurately determined by indirect methods. This value of the solar parallax tells us that the mean distance of the sun from the earth is 92,900,000 miles. There is nothing in the least speculative about these distances. They are found from ordinary measurement of the earth itself and from the measurement of certain angular displacements in the skies. The only assumption that we bring into the argument is that light travels in straight lines.

Seen from the earth, the sun and the moon appear to be about the same size, but since the moon is much nearer to us than the sun it is obviously much smaller. The diameters of these two bodies in miles can be found at once from their known distances and their angular diameters, from the range-finding principle worked backwards. An observer at C who measures the angle ACB and knows the distance PC can calculate AB. In this way we find out that the moon's diameter is 2160 miles, about a quarter of that of the earth; but the sun's diameter is 864,000 miles, rather more than

one hundred times the earth's diameter. If you imagine the earth placed at the centre of the sun there would be plenty of room for the moon to circle round the earth in its present orbit *inside* the sun.

The full list of major planets, as they are known at present, together with their mean distances from the sun, which have been determined by extensions of the trigonometrical method, is as follows:

Planet	Sign	Mean distance from the sun in millions of miles	Period in years	Equatorial Diameter in miles
Mercury	☿	36	0·24	3,000
Venus	♀	67	0·62	7,600
Earth	⊕	93	1·00	7,927
Mars	♂	141	1·88	4,200
Jupiter	♃	483	11·86	88,700
Saturn	♄	886	29·46	75,100
Uranus	♅	1782	84·01	30,900
Neptune	♆	2793	164·79	33,000
Pluto	P	3666	247·70	Unknown

The sun appears featureless to the naked eye (protected by a smoked glass) except on very rare occasions when there is a very large sunspot. When the sun is frequently observed through a large telescope it is found that sunspots are a fairly common occurrence. At some observatories—for instance, at Greenwich—the sun is photographed daily (except in cloudy weather) and the number of sunspots counted and their sizes measured. It is found that there are periods of great sunspot activity followed by periods of little activity, the interval between successive maxima of activity being about eleven years. There is a minimum activity as this book is being written in 1934. Naked eye

spots should be seen from 1936 to 1940. If the sun is inspected with sufficient magnification it can be seen that the solar disc is not perfectly uniform but is mottled. No other phenomena are apparent when the sun is examined in this straightforward way—simply by looking at it, or photographing it—except an occasional bright patch near the sunspots. The sunspots are very large, it is not uncommon to measure one with a diameter of 15,000 miles—in which the earth would be completely lost. I think it is fair to say that in the present state of our knowledge *nobody knows what the sunspots are* and why they occur, though there have been several tentative explanations.

In addition to the major planets there are a great many minor planets—over a thousand have been catalogued—which describe orbits which lie between those of Mars and Jupiter. Some of them are simply colossal boulders, a few miles in diameter and of irregular shape, wandering ceaselessly round the sun.

Mercury is so close to the sun that it can only be seen (except in the early morning) when it is near its greater eastern elongation which happens every four months. At these times it will set about an hour and a half after the sun. It is usually difficult to see the planet in the glare of the sunset; one stands the best chance in the clear atmospheres away from the cities. As will be seen from the list of diameters, Mercury is not much bigger than our moon. Venus, on the other hand can be seen very plainly with the naked eye. When it is near the earth and most conspicuous it is a very brilliant and striking object. Beyond showing phases, like the moon, the planet shows

no well-marked features. Venus is roughly the same size as the earth.

Mars on the other hand has definite markings. The bulk of the planet is red, but there are two well-marked white polar caps, and also many dark markings—the so called "canals". Mars is accompanied by two satellites called Deimos and Phobos, which circle round Mars in the same way as the moon circles round the earth. Mars is considerably smaller than the earth.

Next in order of distance from the sun is Jupiter, the largest of the sun's satellites. Jupiter's diameter is eleven times that of the earth. The planet is a striking sight when viewed through a telescope. Its equator is marked by two dark belts, and there are other markings, notably a large red spot between the two belts, which can be seen under exceptional conditions—that is to say, on a very clear night when the atmosphere is very steady, and with a good telescope. Jupiter has no less than nine satellites, of which four are bright enough to be seen with a small telescope, and are a striking sight. Since the moons circle round the planet roughly in the plane in which we observe them, they occasionally appear to go behind the planet—to be eclipsed. The eclipses of Jupiter's satellites were important for navigation in the days before the development of wireless telegraphy, since the Greenwich times of their disappearances could be predicted accurately, and are published in advance in the Nautical Almanac. The navigator who wished to determine his longitude by comparing local time, as he observed it, with Greenwich time, shown by his chronometer, could determine the error of his chronometer by comparing the chronometer time of an eclipse with

the Greenwich time as shown in the almanac. Jupiter's satellites performed an interesting service in the development of physics, as the velocity of light was first determined from observations of their motions. The astronomer Römer noticed that when he observed

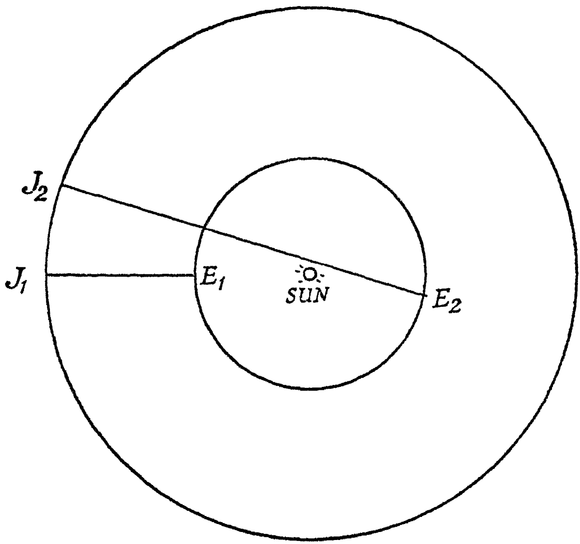


FIG. 10.—The velocity of light from the eclipses of Jupiter's satellites. Light takes longer to get from J_2 to E_2 than it takes to get from J_1 to E_1 by an amount nearly equal to the time it takes to travel across a diameter of the earth's orbit, or 180 million miles. (The planetary orbits have been drawn circular for simplicity.)

their rates of revolution at a time when Jupiter was close to the earth and calculated their positions for the time when Jupiter was at its farthest point from the earth, the moons arrived at the expected position sixteen minutes, or nearly 1000 seconds, too late; he deduced, correctly, that this apparent lateness was the time taken for the light to travel across the extra dis-

tance, which is twice the radius of the earth's orbit, or 186,000,000 miles, so that the velocity of light in vacuo is 186,000 miles per second (fig. 10).

The next planet, Saturn, is the most striking telescopic object of all the planets. In addition to its nine moons (which are rather faint) Saturn is encircled by rings which are concentric with the planet. Saturn is not quite so big as Jupiter, but is a good second in size in the sun's family. Both Jupiter and Saturn have long periods (11·9 years and 29·5 years respectively) and accordingly do not appear to travel very far in right ascension during the terrestrial year, so that they can be seen to advantage—when they are on the opposite side of the earth from the sun—at intervals of nearly one year each. If you notice either Jupiter or Saturn prominent in the midnight sky, it will be too near the sun to be seen in six months' time, and will be conspicuous again in a further six months.

The major planets, from Mercury to Saturn, have been known since classical antiquity, but the next three planets were unknown in the early eighteenth century. Uranus was discovered by Herschel in 1781. He wished to name the planet *Georgium Sidus* in honour of his patron, King George III, but he was persuaded to adopt the present name, which is in harmony with the series of names used for the other planets. Although Uranus is much larger than the earth it is so remote from the sun that it is too faint to be seen with the naked eye—except, perhaps, to a person with very keen eyesight in a very clear atmosphere. I am told that some South African natives can distinguish Jupiter's moons with the naked eye. Jupiter's moons appear brighter than the planet Uranus, but the

nearness of the very bright planet makes them difficult to see. On the other hand you would have to know exactly where to look for Uranus in order to have any chance of picking it out.

Although the chief gravitational influence which is exerted on each of the planets is the pull of the sun, the planets attract each other to a much smaller degree, and these small influences have measurable effects on their motions. Jupiter as the largest planet is generally responsible for the largest part of these *perturbations*, as they are called. When allowances were made for the perturbations the observed movements of the planets in the eighteenth and early nineteenth centuries fitted in pretty well with Newtonian dynamical theory—all except Uranus, which declined to proceed accurately along a Newtonian orbit. It occurred to Adams, then (in 1845) a young man at Cambridge, to investigate whether the peculiar behaviour of Uranus was not due to perturbation produced by a hitherto undiscovered planet lying still farther from the sun. Adams solved the problem of accounting for the observed movement of Uranus and even deduced, from Newtonian dynamics, where the perturbing planet should be. He asked various English astronomers to look for the expected planet in a certain region of the heavens. Unfortunately, the English astronomers failed to do credit to themselves on this occasion. Sir George Airy, then Astronomer Royal, offered only lukewarm support to Adams. Challis, Professor at Cambridge, looked for the planet and after some delay found it, but he only did so after it had been discovered by Galle, who had been told to look for it by Le Verrier, who had done the same theoretical

work as Adams and arrived quite independently at the same conclusion. Whether the immediate credit was due to Adams or to Le Verrier there could be no doubt that the discovery of the planet—now called Neptune—in consequence of the predictions of Newtonian planetary theory was a signal triumph for astronomy, and as such it was hailed by an appreciative decade. Neptune is very faint, and very remote. Nothing about the planet has proved so remarkable as the manner of its discovery. The motions of Neptune were analysed in the present century with the object of discovering in the same manner a possible extra-Neptunian planet. These labours have been rewarded by the discovery, in 1930, of the still fainter and still more remote Pluto. There may very well be still more and still fainter planets farther removed from the sun.

It is fashionable, in writing a book of this kind, to give the reader a scale model of the solar system, so that he may the more easily envisage the relative sizes of the sun and its planets, and the relative distances between them. Very well, then; let us construct such a model. Choosing the scale to be such that the diameter of the model sun is one foot—a rather large football—the largest planet, Jupiter, is about the size of a billiard ball, and Saturn is a little smaller. The next two planets, in size, are Neptune and Uranus, which are about half an inch in diameter in the model. They could conveniently be represented by moth balls. The earth, Venus, and Mars are about the size of sweet pea seeds, and little Mercury brings up the rear as a very much undersized sweet pea seed—perhaps we might take a pin's head as our model of Mercury. We should need a large heath on which to distribute

the models in their proper relations to the football sun, as our model of Neptune should be a thousand yards—just over half a mile—away from it. The model Jupiter should be placed five hundred feet from the sun, and the model earth a hundred feet; and the other model planets spaced out proportionately between Neptune and the sun. In this model a pin-head moon travels round the model earth in a circular orbit of about three inches radius.

The models have all been laid out on a heath, which implies that the planets travel round the sun in the same plane. If they did this they would always be seen on the ecliptic. This is not actually the case. The orbits of the major planets are slightly inclined to the ecliptic. Mercury's orbit is the most sharply inclined, but even in this case the inclination is only seven degrees. Next comes Venus—with an inclination of three degrees and a half. The inclinations of the rest range from 2° 36′ (Saturn) to 0° 46′ (Uranus), so that a flat model is not a grave distortion of the observed facts.

Besides the major planets and minor planets, the sun's retinue embraces another class of wanderers—the comets. There has been no comet large enough to attract the attention of the casual observer since the last appearance of Halley's comet in 1910, and no very bright ones are expected in the near future. There are always a few very faint comets to be seen in every year with the aid of a large telescope. Some of these objects move in highly elliptical orbits, at one end of which they are fairly close to the sun and, incidentally, to the earth, so that they are well seen; but at the far end of their orbits they are very remote, far out

beyond Neptune and even Pluto, and as they are not intrinsically very bright they cannot be seen at all. This is the case with *Halley's comet.* It was observed by Halley, in 1682, and he found that its orbit was very similar to the orbits of comets observed by Kepler and Apian in 1607 and 1531, and he found further that bright comets had been recorded in the past in 1456, 1301, 1145, and 1066. He noticed that the two intervals between 1531 and 1607 and between 1607 and 1682 were not quite equal, but he satisfied himself that the disturbance was due to the attraction of Jupiter and Saturn. Halley decided that all these apparitions were of one and the same comet, and predicted its return in 1759, when it was again seen. The comet has since appeared in 1835 and 1910. It will not be seen again until 1987. Recent research has unearthed in various ancient chronicles a record of every one of the twenty-seven apparitions that the comet has made between 87 B.C. and 1910 A.D.

Comets are distinguished by the possession of a tail—a great cloud of hazy luminous matter travelling through space with the nucleus. The tail is usually fan shaped, and very long; lengths of from 30 to 50 million miles are not uncommon among bright comets. These tails are extremely tenuous; it is suspected that the earth actually passed through the tail of Halley's comet on 21st May, 1910—and it made no difference to anybody.

Lastly among the bodies which are found within the solar system we come to the meteors, or "shooting stars". They are not stars at all, but lumps of stone and iron of various sizes which float about space; they are quite invisible until they collide with the

earth's atmosphere, then they burst into flames. In most cases they burn out completely before striking the earth, but occasionally one gets to earth incompletely burnt. These bodies exhibit large parallaxes; if a shooting star is seen by two observers twenty miles apart they will record the beginning of its flight as being in quite different constellations. If a meteor is seen by a number of observers at different stations each of whom records the apparent position of the beginning and end of its track, it is possible to construct the actual path; such paths are generally found to be from fifty to twenty miles above the surface of the earth.

We may finish this chapter by touching on the vexed question, is there any life on the planets? Astronomers do not know. The irregularities of refraction in the earth's atmosphere prevent us from making very detailed examinations of planetary surfaces, even with our most powerful telescopes. It should be added that the spectrograph (Chapter V) gives an indication of the composition of the atmospheres carried by the planets. In the case of Mercury, the planet is so small that the force of gravity is insufficient to retain an atmosphere. (It is its *weight* which prevents the air we breathe from wandering off into space.) Mercury is a dead planet like our moon. Venus has neither oxygen nor water, but it does have carbon dioxide, which shows that plants, if any, are not numerous. Without plant life there can be no animals or human beings. Mars is so small and its gravity so weak that its atmosphere is thin. It has polar caps, suggesting water, but the spectrum shows no oxygen. The outer planets have temperatures far below zero,

and their great masses enable them to hold dense atmospheres, containing gases which are rare in our atmosphere. The poisonous gas ammonia is an abundant constituent of their atmospheres, and oxygen has not been found in any of them. We can fairly say that it is very unlikely that any of our neighbours support any life remotely like our own, and we must warn imaginative enthusiasts who project interplanetary journeys in rockets that they must carry gas masks and an adequate supply of oxygen if they are to avoid suffocation at the end of their journey.

CHAPTER III

Stellar Distances and Magnitudes

THE range-finding process applied to the moon, using the earth's diameter as a base, gives no result at all when applied to the stars. But we can avail ourselves of a much longer base than that, namely, the diameter of the earth's orbit. Some of the stars are near enough to show a measurable parallax when observed at intervals six months apart (fig. 11).

Very accurate meridian work would show up a large parallax. Suppose that a star which has a large parallax is seen in the summer as an evening star and in the winter as an early morning star. Then the right ascension of the star will appear to alter slightly from summer to winter—the right ascension being the angle between the line joining the earth to the star and a fixed direction, the direction of the equinox. Meridian observations are technically unsuitable for the determination of parallax because certain systematic errors in the meridian work may be falsely identified with parallax, and the practical success of this method of measuring stellar distances depends on the fact that most of the stars are so far off that they show no parallax, so that the line joining the earth to the distant star is practically a fixed direction. The first reliable measurement of parallax was made by Bessel

in 1838 who carefully compared the position of the star 61 Cygni with those of neighbouring stars. The parallax of this star is three-tenths of a second of arc,* which means that the distance of the star from the sun is 688,000 times the radius of the earth's orbit, which is itself 93 million miles; so that the distance from the sun to 61 Cygni is about 64,000,000,000,000 miles,

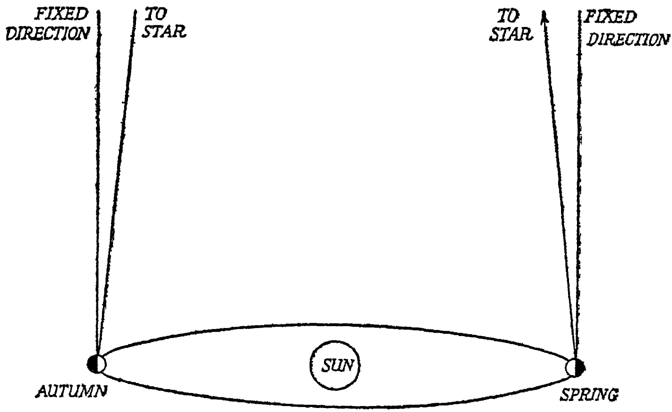


Fig. 11.—Measurement of a star's distance

and 61 Cygni is one of the closest stars. One can comprehend easily enough the distances from one continent to another—from London to New York—as large compared with a statute mile. The distance from the earth to the sun is again very large compared with an inter-continental distance; but the distance from the sun to even the nearest star is a quantity of

* For the reader who has forgotten his mathematics, the right angle is divided into ninety degrees; each degree is divided into sixty minutes (of arc), and each minute into sixty seconds (of arc, as distinct from seconds of time). The full moon subtends an angle of about thirty minutes to our eyes. A second of arc is, roughly, the angle subtended by an object an inch long—a halfpenny—to an observer four miles away.

yet another order of magnitude. Light is the fastest moving thing that is known; it travels with a velocity of 186,000 miles a second and so would take less than two hundredths of a second to travel from London to New York. (This is roughly the time it takes a wireless time signal to get from Greenwich to Washington.) The sun is so far from the earth that it takes eight minutes for light to pass from the sun to the earth. But it takes *eleven years* for the light to reach the earth from 61 Cygni.

The general public are used to being told extraordinary things by scientists; the man in the street is told that 61 Cygni is 64,000,000,000,000 miles away from him, and that the hydrogen atom weighs 0.00000000000000000000000166 grammes, and he believes both statements; he is on this account frequently accused, by those who deplore the scientific tendencies of this age, of being credulous—much more credulous than members of the mediæval public, who lent a ready ear to tales of supernatural happenings. Why does the intelligent layman believe the "fairy tales" of science? For one thing, science has produced some very impressive results which anyone can appreciate—for example, that nearly incredible machine, the radio. But there is a much more important distinction between science and nonsense than mere ability to produce impressive toys. Scientific facts are demonstrable, and open to inspection and criticism by all those who are interested. If you do not believe that 61 Cygni is so far off, measure its parallax yourself. If the parallax—or rather, absence of a large parallax—could only be seen by astronomical "mediums" there would be some justification for stigmatizing those

who believe in stellar distances as being credulous, but anybody who likes to take the trouble can verify the facts of science in general and of stellar distance in particular.

Parallaxes are now determined photographically. The astronomer photographs a field of stars in the evening sky. Six months later he photographs the same field in the early morning sky. Then if one of the stars is near enough to have a measurable parallax it will have shifted its position relative to the comparison stars. The shift is measured and the parallax of the star calculated. It is, of course, usual to measure several pairs of plates for each parallax star, in order to compare the results and eliminate accidental errors as far as possible. Thousands of parallaxes have been measured in this way. The probable error of a determination of parallax of this kind is usually between five and ten thousandths of a second of arc, so that parallaxes can only be considered to be well determined when they exceed two- or three-tenths of a second of arc. When stars are so far removed from us that their parallax is smaller than a hundredth of a second of arc, the direct method of trigonometrical parallax, as it is called, will not tell us their distance at all accurately.

The nearest star is called Proxima Centauri. Its parallax is $0''\cdot765$, so that its distance from us is 25,300,000,000,000 miles, a distance which it takes 4·3 years for light to travel. This star is close to the bright star α Centauri, which is about the same distance away from us. The brightest of the stars, Sirius, has a parallax of $0''\cdot371$, and is 8·8 light years away. (One light year = 5,880,000,000,000 miles.) Of the bright stars, Procyon comes next, with a parallax of $0''\cdot312$

being 10·4 light years away. Farthest away of the very bright stars is Canopus, the second brightest star in the whole sky. (It is a southern star, invisible in England.) Its parallax is $0''\cdot005$—too small to be measured accurately, but supposing this figure to be correct, Canopus is about six hundred light years away. As it appears so very bright in spite of its great distance it must be intrinsically a very bright star indeed.

To avoid reproducing very large numbers, astronomers make use of a very large unit of distance called a parsec. When an object is one parsec away it has a parallax of one second of arc, so that the parsec is 19,160,000,000,000 miles. Another unit which is sometimes used is the light-year, the distance travelled by light in one year, which is 5,880,000,000,000 miles. One parsec equals 3·26 light-years. Proxima Centauri is accordingly distant 1·3 parsecs or 4·3 light-years; the smaller figures are much more convenient to handle, but it must not be forgotten that the units are immense.

This brings us to the notion of stellar brightnesses, or stellar magnitudes, as they are called. A glance at the sky makes it apparent that the stars do not appear to be equally bright. This being so it becomes the task of the astronomer to measure the relative brightnesses of the stars. The stars are assigned *magnitudes* following upon a very ancient practice. Hipparchus and Ptolemy arbitrarily graded the stars into six magnitudes, the sixth magnitude being the faintest visible to the naked eye, and the first magnitude comprising about twenty of the brightest stars.

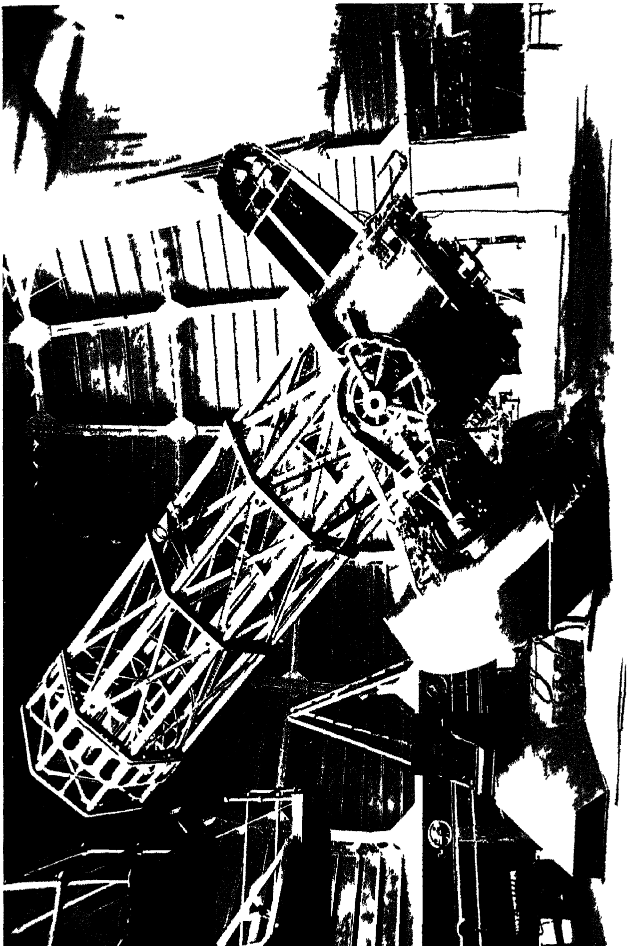
About the year 1830 Sir John Herschel discovered that stars of the first magnitude are about one hundred

times as bright as stars of the sixth magnitude, and the magnitudes are now defined on this basis; a star whose magnitude is said to be 6 sends to us one-hundredth of the light from a star whose magnitude is said to be 1; similarly, we receive from a 7th magnitude star one hundredth the amount of light that we receive from a 2nd magnitude star, and so on. In exact work decimals of a magnitude are employed; and if a star sends us one hundred times as much light as the standard first magnitude star it has a negative magnitude—minus four. On this rather odd scale (a logarithmic scale) the sun's magnitude is −26·7; that of Venus is −4; of the full moon, −12·5. Only two stars have negative apparent magnitudes, Sirius (−1·58) and Canopus (−0·86). The first magnitude stars (0 to 1) are (in order of brightness) α Centauri, Vega, Capella, Arcturus, Rigel, Procyon, α Eridani, β Centauri, Altair, and Betelgeuse. Amongst the second magnitude stars are to be found Aldebaran, Pollux, Spica, Regulus and Castor. Altogether, there are 530 stars brighter than the magnitude 4·0, and 4850 stars visible to the naked eye—a naked eye that can see just down to magnitude 6·0. This is probably a smaller figure than the reader had imagined. But let him take comfort in the estimate that there are 1,000,000,000 stars brighter than magnitude 20·0.

Stellar magnitudes are usually measured photographically. When a field of stars is focussed on to a photographic plate, the brighter stars will make larger and darker markings on the negative than the fainter ones. By making a careful study of the behaviour of the photographic plate one can determine the amount of blackening which it will register on

receiving a given amount of light, and so calibrate the star magnitudes; but it is a very complicated matter in practice, as the colours of the stars have to be taken into account, the various colours affecting the negative to a greater or less degree. Another instrument for recording light received is the *photo-electric cell.* Certain metals possess the property that they emit electrons when light is radiated on their surfaces. If one makes a little cell with such a metal in a vacuum and attempts to pass an electric current from the metal to another terminal there will be no result unless light falls on the metal, when the electrons which it emits will carry the current. The strength of the current is a measure of the amount of light falling on the photo-electric cell. This method is a new one, but it holds out some promise of becoming efficient and accurate.

Now a luminous object may look bright for one of two reasons: because it is very close to you, or because it is a very bright light indeed. A pocket torch a few feet away looks much brighter than a car's headlights half a mile off. To get any measurement of the absolute brightness of a source of light we must find out how bright it looks when at a standard distance from the observer. Line up the pocket torches and the headlights a quarter of a mile away, and you will easily pick out the bright lights from the faint. We do the same—in theory—with the stars. To compare their intrinsic brightness, we calculate what their brightness would be if they were a standard distance away; the magnitudes which the stars would have if they were lined up at the standard distance of 10 parsecs are called their absolute magnitudes.



E 846

60-INCH REFLECTING TELESCOPE AT MOUNT WILSON OBSERVATORY, WITH A SPECTROGRAPH IN POSITION

The absolute magnitude can be found from the apparent magnitude if the parallax is known, the law connecting the distance of an object with its apparent brightness being the inverse square law: (if there are two similar objects, one twice as far away from the observer as the other, the nearer looks four times as bright as the farther.)

The bright star which comes out of this test with the most credit is Canopus. Although it is apparently not so bright as Sirius, it is a great deal farther off, and it heads the list with the absolute magnitude of $-7{\cdot}4$. Sirius is really nowhere near the brightest in absolute magnitude ($+1{\cdot}3$). The second magnitude star Regulus is much brighter than Sirius intrinsically, and its absolute magnitude is $-2{\cdot}5$. The magnitude scale has something of an Alice-through-the-looking-glass air about it; the minus magnitudes are the brightest stars.

Of the bright stars visible in the northern hemisphere, β Orionis, (Rigel) heads the list of absolute magnitudes with $-5{\cdot}8$; close behind it is α Cygni (Deneb) with $-5{\cdot}2$.

The sun, by the way, would look an indifferent body in the imagined test. If the sun was removed to the inspection line, its apparent magnitude would be $+5{\cdot}0$; that is to say, it would be almost too faint to be seen with the naked eye in England, except under very good conditions. Canopus at the same distance would look about ten times as bright as we see Venus at its brightest. It need hardly be said that the largest *planet*—Jupiter—translated to this enormous distance (10 parsecs) would be completely invisible even with the largest telescopes in existence. Since the stars are

so far away from us as they are, we have no hope, at present, of finding out whether any of them are accompanied by planets, like our own sun, or not.

A large number of the stars which appear single to the naked eye are seen on examination with a telescope to be double stars. These stars exhibit one enormously interesting property: they rotate round a common centre of gravity in elliptical orbits in accordance with the laws of Newtonian dynamics. By making a painstaking series of observations of a double star extending over years, the astronomer can trace the apparent motion of the stars and determine their orbits. If the parallax of the pair of stars is known, one can convert the apparent size of the orbit, in seconds of arc, into the actual size of the orbit in miles, and if the radius of an orbit and the period which it takes to describe it are known, one can calculate the mass of the attracting body from the laws of Newtonian dynamics. Our analogy to orbital motion was a stone being swung round one's head by a piece of string. The faster the stone is being swung round, the harder must the string pull at it; and the longer the string, the greater must be the pull—for a given time of swinging right round. The curious may like to verify these facts; we must caution them to tie the rotated body very securely to the string! In the celestial case of orbital motion, the more extended the orbit, and the faster it is described, the greater must be the attracting force between the two bodies; and this attracting force is simply proportional to the sum of the masses of the two bodies. This sum can, then, be found if the radius of the double-star orbit can be found from a well determined parallax, the period, of course, always being well known.

The first double star was discovered by Riccioli in 1650; it was ζ Ursae Majoris, one of the Plough stars. One can see two stars with the naked eye; there are really three, the brighter of the two being resolvable into two distinct components with a small telescope. The period of a double star—the time it takes the two components to get once round their respective orbits—may be almost anything. Capella is a double star in which the pair rotates in three and a half months; Castor is a double star with a period of over three hundred years. Naturally, the longer the period, the longer it takes the double star to describe its orbit; and if the period is 1000 years, and we have only been interested in observing such things for about a century, we have as yet had no chance to see it go completely round its orbit. By the time we have seen one half of the orbit we can deduce the other half with confidence; but there is not much hope of finding the orbits of the binary stars with periods of 1000 years or more for a century or two yet!

In the case of a body which has a satellite describing a circular orbit of radius R in time T years, Newtonian dynamics shows that the mass of the primary body is proportional to R cubed divided by T squared. We can find the mass of a star which has a small companion in terms of the sun's mass by making the unit of R equal to the radius of the earth's orbit. In the first place, it is noticed that among the known double stars it is a general rule that the further apart the two stars are, the longer the period—which means that the stars have all more or less the same mass. (Mass is called weight in everyday speech. There are two separate scientific concepts labelled *mass* and *weight* which are

not distinguished in everyday speech; we use weight for both. But I must not upset my scientific friends by using "weight" instead of "mass" if to do so would be technically incorrect, so "mass" it must be, and if the reader likes, he can think of it as "weight", unless and until he acquires an interest in dynamics.)

Now there is no *a priori* reason why the stars should have anything like the same masses. There is no difficulty in imagining a star 1000 times as massive as the sun (Canopus is 10,000 times as bright) or a star having one-thousandth of the sun's mass; but the lightest known star is about half the sun's mass and the heaviest fifty times. (The sun's mass, found by the application of Newtonian gravitational theory to the radii and periods of the planetary orbits, is 2,000,000,000,000,000,000,000,000,000 tons.) The two components of Capella together weigh as much as 7·5 suns; those of Sirius, 3·4 suns; and in the case of Procyon, one and a half times the sun's mass is to be divided between the two components. While it is recognized that this limitation which Nature seems to impose on the possible masses which stars may have is very significant, no complete interpretation of it has as yet been made.

The study of the positions of the stars has yielded proof of another kind of stellar movement, in addition to the parallactic movement and the orbital movement of double stars; this third movement is called proper motion and is the actual movement of the star itself as it moves through space. There is nothing to keep the stars fixed. They look fixed enough from night to night or even from year to year, if you do not measure their positions too closely; but their apparent

fixity is due to their enormous distance from us. When a thing is far off it has to move a lot for you to see that it has moved at all. Imagine a sailing ship, becalmed, out at sea on a fine windless day. She may be drifting, perhaps she is not. The best way to tell is to set up two marks on the shore in line with the present position of the ship; if she is drifting, presently you will see her out of line with your marks. What mark can we set up to see whether a star has drifted? There are two: the other stars, and the equinox. Taking the last-mentioned system of marking first, the position of the equinox—the direction in the sky where the sun crosses the equator—can be found with the transit circle; with the same transit circle the right ascension and declinations of the stars—their astronomical longitudes and latitudes—are carefully recorded. Ten, twenty or thirty years afterwards the work is done all over again. It is found that the equinox has shifted, but the shift has been studied so long that we know how to allow for that; and it is found that some of the stars will have shifted appreciably in right ascension and declination over and above the shift of the equinox. In a general way it is usually the stars which have large parallaxes which have shifted most, and the faint stars which are too far off to show a parallax are too far off to show a proper motion—not always, though; the motions are distributed (very nearly) at random, and some stars which are close to us are not moving very fast, and some which are a long way off *are* moving very fast, fast enough for us to detect the proper motion even when the parallax is too small to be measured. In this kind of work, the longer one waits the more chance there is of detecting proper

motions and the more accurate is one's measurement of the motion; just as in our analogy of the ship becalmed, if you come back to the marks after a minute you may not see any shift, but after an hour's wait you are very likely to detect it; and the farther out to sea, the longer must you wait to see the result of the ship's movement. So it is with the observations of the stars; working over a catalogue thirty years old gives the astronomer a fair chance to observe individual shifts.

Since the faint stars show very little proper motion, a way of finding proper motions is to measure the shift in a ten-year's interval of a bright star relative to a background of faint stars. This method is often employed; it is carried out photographically. A certain field of faint stars including one bright star is photographed, and ten years later the same star field is photographed with the same telescope; the movement of the bright stars relative to the faint stars during the ten years that have elapsed is then measured.

The annual proper motion of α Centauri is $3''\cdot682$—a figure not exceeded by many stars, by none brighter than the fourth magnitude. α Centauri might have been expected to show a large proper motion since it is one of the nearest stars. The annual motion of $3''\cdot682$ corresponds to a velocity of twelve and a half miles per second. Arcturus shows a proper motion rather less than α Centauri, namely, $2''\cdot287$ per annum; but as Arcturus is much farther away—about ten times as far off as α Centauri—it is really moving much faster, the speed being about eighty-four miles per second—a feeble velocity in comparison with the velocity of light, perhaps. Here are no long strings of

o's to amaze the reader. Still, it is a tidy speed for so massive a vehicle.

When we speak of velocities we must mean velocities relative to something. It is perhaps hardly necessary to labour this point in the present day, when a memory of something of the sort clings to a public which took its Einstein seriously only a decade ago. In these cases we mean velocities relative to the sun. The question arises, is the sun itself moving, to which must be put the counter question, *relative* to what frame of reference do you ask whether the sun moves? Let us take the centre of gravity of the stars as a reference point. Then the sun does move—carrying, of course, the earth, planets and comets, which are oblivious of the sun's motion, along with it. We can only find out the solar motion by analysing the proper motions of as many stars as we can get, and testing their movements for an apparent common trend in a particular motion; this trend which they all share is the equal and opposite of the solar motion, though each star imposes on the general trend the particular movement of its own. It is as if it looked out of an aeroplane and saw a lot of people running about on the ground. If they are running about in all directions the motion of each relative to the aeroplane will depend on his particular gait and the direction in which he chooses to run, but taken as a whole their average speed towards the aeroplane will be simply the speed of the aeroplane towards a fixed point among them on the earth.

Relative to the stars as a whole the sun has a velocity of twelve miles per second, and it is moving towards a point in the constellation Hercules. All the same the sun is not rushing headlong to destruction; not, at

any rate, in our time. Even if we were directed precisely in the direction of the nearest star it would take us fifty thousand years to get there; and there is so little crowding among the stars that we can travel much longer than that with but little probability of encountering anything more substantial than harmless comets and meteors.

Most of the constellations are chance collections of stars that have nothing to do with one another, and only appear in the same direction from our view point. When their proper motions are examined it is found that they are moving in different directions independent of one another; but there are certain clusters of stars moving together. The only notable constellation which is a connected group like this is the Plough part of Ursa Major; five out of the seven Plough stars have very similar proper motions and are undoubtedly a connected group of stars pursuing a common course through space. There are many clusters of stars which are visible with small telescopes; these clusters are very interesting collections of stars, and they vary considerably in general appearance—in the faintness of the stars and in the number of them in the cluster.

Not all the stars shine from night to night with the same brightness. A great many of them are variable. The brightest variable star is Betelguese, which varies from $0^{m}\cdot 5$ to $1^{m}\cdot 1$ in apparent magnitude, and the most striking range of variation among the brighter stars is o Ceti, whose apparent magnitude ranges from $2^{m}\cdot 0$ to $9^{m}\cdot 6$. At its brightest it is a conspicuous star, and at its faintest it is by several magnitudes fainter than any naked eye star, the range of 7·6 magnitudes meaning a variation of a thousandfold in the light which

the star emits. This star is called Mira Ceti, as well it may be. Other bright stars which are variable are α Cassiopeiæ, the second of the five stars in the W to cross the meridian. It is sometimes brighter than either of its neighbours, β and γ Cassiopeiæ, and sometimes fainter than either; Algol, or β Persei, varies from $2^m \cdot 3$ to $3^m \cdot 5$, a conspicuous change.

The variation in a variable star's apparent magnitude can be due to one of a number of causes; and the variable stars are stars as classified according to the nature of the light variation. In the first class come the Algol variables, or eclipsing binaries. The variations in Algol's brightness, which were first noticed in 1670, are periodic and occur at regular intervals of 2 days 20 hours 48 minutes. For about 2 days and 11 hours the star remains steadily bright; during the next five hours it loses two-thirds of its light and in another five hours regains it again. The explanation put upon this phenomenon is that Algol is really a double star, the components of which are too close together to be separated; but the plane of the orbit of this double star happens to coincide with the plane in which we see it, so that one star eclipses the other at regular intervals. The fainter star gets in front of the brighter and cuts off its light once in every passage round the orbit, so that the period of the light variation, 2 days 20 hours 49 minutes, is the time taken to describe the orbit. Ordinarily we see the light from both stars; at the time of eclipse the brighter star is obscured. (There is also a secondary minimum when the faint star is obscured by the brighter.)

Algol is marked on the map of the appropriate part of the sky in fig. 12. The constellation Perseus is well

placed in the evening sky in the winter; the dates on which the different parts of the sky are in the meridian at 9 p.m. are marked. On 21st December, for example, at 9 p.m. the northern part of the constellation Perseus is directly overhead at Greenwich, and Algol is on the meridian ten degrees south of the zenith. Aldebaran, Capella and the Pleiades should help you to find Algol quickly. Ordinarily it is the brightest star for some little distance round, but at its minimum it is no brighter than δ Persei, just south of it. The magnitudes of the stars near Perseus are marked on the map. The best chances to see the eclipse of Algol during the next few years are as follows:

ALGOL

Greenwich Mean Times of Winter Evening Eclipses

1939	hours	1940	hours	1941	hours	1942	hours
Nov. 16	24	Nov. 17	24	Nov. 2	20	Nov. 2	24
,, 19	21	,, 20	21	,, 22	22	,, 5	20
,, 22	18	,, 23	18	,, 25	19	,, 25	22
Dec. 9	22	Dec. 10	23	Dec. 12	24	,, 28	19
,, 12	19	,, 13	20	,, 15	20	Dec. 14	24
,, 29	24	1941		,, 18	17	,, 17	20
1940		Jan. 2	21	1942		1943	
Jan. 1	21	,, 5	18	Jan. 4	22	Jan. 6	22
,, 4	17	,, 22	23	,, 7	19	,, 9	19
,, 21	23	,, 25	20	,, 24	24	,, 26	24
,, 24	19			,, 27	20	,, 29	21

These times are all expressed on the twenty-four-hour system: 18 hours is 6 p.m., etc., up to 24 hours which is midnight.

The times shown are the Greenwich times of full eclipse to the nearest hour. The darkening and recovery are most noticeable one and a half hours before and one and a half hours after this minimum. Another star map on p. 3 shows where to look for Mira Ceti.

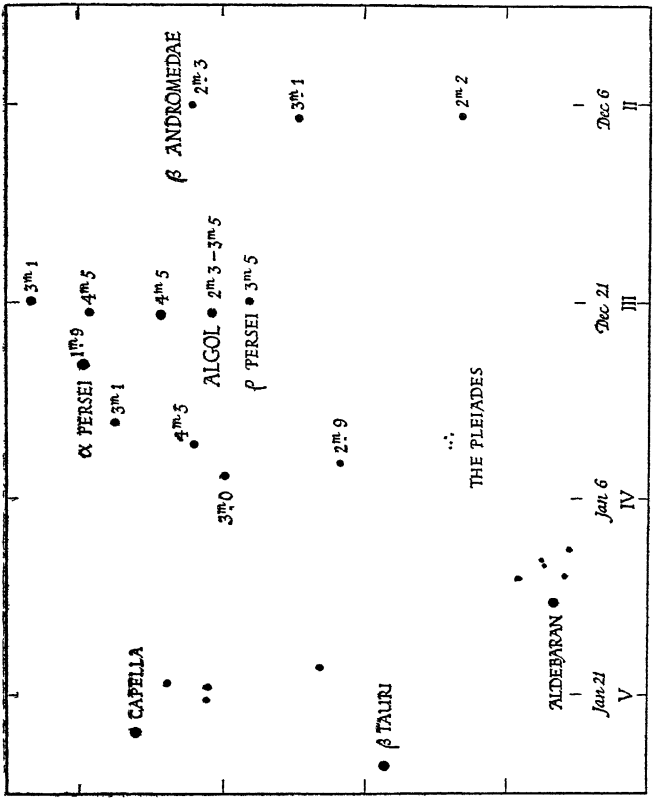


Fig. 12.—Map to find Algol

Its period averages about 330 days, so that there is no sudden change to observe. Like Algol, Mira Ceti is a winter star. If a watch is kept from about November to January, some change in Mira Ceti should be seen, but in some years, of course, the winter months will coincide with the minimum of Mira Ceti and one will see nothing at all in the expected place.

Maxima took place, or are expected, as follows: 27th November, 1935; 24th October, 1937; 21st September, 1937; 20th August, 1938; 6th August, 1939; 4th July, 1940; 31st May, 1941; 28th April, 1942; 26th March, 1943; 21st February, 1944; 18th January, 1945, &c.; the period is irregular but averages 332 days. This means that Mira Ceti will be conspicuous in the evening winter skies in 1945, and will be fainter—when the constellation is looked for in the winter—every year, as the maximum creeps round into the summer. Not all the variable stars are eclipsing variables, by any means. (Mira Ceti is not one.) The Algol variables exhibit a constant brightness except for short interruptions at the time of eclipse, but the other variables show a periodic variation which is going on in one way or the other all the time, like a pendulum swinging backwards and forwards. It is supposed that these variables are single stars, and that in some cases, at any rate, the star is pulsating—that is to say, alternately expanding and contracting. The pulsation is accompanied by variations of surface temperature, and so of surface brightness. The pulsating stars are called Cepheid variables, the type taking its name from δ Cephei, which has a period of five and a half days in the course of which the star's brightness falls very abruptly from $3^{m}\cdot 7$ to $4^{m}\cdot 4$ in about one day and a half and then climbs slowly back to maximum in the remaining four

days. When brightest, δ Cephei is nearly as bright as ζ Cephei, and when faintest, it is noticeably fainter than ζ and about the same brightness as its other neighbour ε Cephei. Cepheus being a northern constellation it can be seen in England at all times of the year, but it is highest in the sky in the evening in the autumn months. If you keep a diligent watch on the constellation you may be rewarded by seeing δ Cephei comparable with ζ Cephei on one night and with ε Cephei on the next. The stars can be identified on the figure on p. 7. Another star which shows this sort of variation is ζ Geminorum, but the range of variation in its light is only about half that of the type-star, so that keener observation will be necessary to detect any change. The Cepheid variables have afforded astronomers a great deal of interest; partly in the way of arguing what they really were, and whether a star could and did pulsate; but also because they exhibit a special property which enables us to use them to measure very great distances, far greater than those which can be measured by the direct method of trigonometrical parallaxes.

This range-giving property of the Cepheids consists in their *period-luminosity relation.* It is an observed fact that among Cepheids the period depends on the absolute magnitude, so that if you observe a Cepheid variable and find out its period in days, you can tell its absolute magnitude from your experience of the behaviour of known Cepheids. You can also observe how bright it appears to be—its apparent magnitude. The ratio of the absolute magnitude to the apparent magnitude then gives the distance of the star. It is as if there were an arrangement among the makers of lighthouses that they would grade the lights in order of brightness; the lowest grade are to wink five times

a minute, the next four times a minute, and so on, the brightest winking only once a minute. Without this arrangement a mariner could not tell whether he was confronted with a very bright light ten miles off, or a fainter light only five miles off, or even a feeble one a mile off; but with the period-luminosity law for lighthouses, our sea captain would count the number of winks a minute. It winks, we will say, once. Then our captain knows that it is a very bright light, so that if it looks faint, it must be a long way off. Or it winks five times; then he had better keep clear of it, it is a faint light, quite close.

We do not yet know why the Cepheids exhibit this property, but it is very useful that they do, as we are enabled to extend our survey of the universe to enormous distances by observing the degree of faintness to which the Cepheids have attained. For example, the *globular clusters* contain Cepheids. These globular clusters contain about fifty thousand stars each; the nearest of them appears to the naked eye as a single star, ω Centauri.

It might be expected from the very large number of stars in each globular cluster that they are very far off, so that the stars are not really packed tightly together. The Cepheids in them show this to be the case. For example, ω Centauri is shown by the Cepheids in it to have a parallax of $0''{\cdot}00015$, so that it is 6500 parsecs away. The central, dense part of the cluster is accordingly about 5 parsecs in diameter; so that the clusters are much more crowded than space near the sun. There are only nineteen stars (counting the sun as one) inside an imaginary sphere of diameter eight parsecs centred on the sun.

Last but not least among the variable stars come the Novæ. Every now and then—perhaps half a dozen times in a quarter century—one of the ordinary stars will suddenly flare up and increase its brightness by ten or twelve magnitudes; a star which by reason of its great distance appears very faint will suddenly explode, and in a few days time emit a hundred thousand times as much light as before. Tycho Brahe observed a Nova in the constellation Cassiopeiæ in 1572, which became brighter than Venus; indeed, it was visible in the daytime for a few days, after which it gradually waned and eventually became invisible to the naked eye. There have been eight Novæ since 1900 of which the brightest appearance was presented by a Nova which appeared in the constellation Aquila in the year 1918. This star was originally of the eleventh magnitude, and remained so until 5th June, 1918; but on 7th June it had increased its magnitude to the sixth magnitude; on 8th June it had reached the first magnitude, and on 9th June its magnitude was $-0{\cdot}5$, so that it was brighter than anything in the northern hemisphere except Sirius (which happens to be invisible at that time of the year). This prodigal expenditure of energy did not last for very long, and the star dropped back five magnitudes in three weeks. Six months after the outburst the star was no longer visible to the naked eye.

Nobody knows when or where the next Nova is going to come; the discovery of a Nova is often made by an amateur who has a good knowledge of the constellations and notices an unfamiliar object in the sky. When a Nova is found no time is lost in examining the outburst, and the subsequent history of the star

is always followed up by the great observatories of the world, but, unfortunately, from the nature of the case it is impossible to make a special study of a Nova *before* its outburst as nobody knows among which of the many faint stars—too faint to have been caught in the net of systematic investigation—the outburst will occur.

CHAPTER IV

The Temperatures of the Stars

SO far, we have considered the stars as moving bodies, and we have shown how their masses can be determined. But astronomers have not been satisfied with this kind of knowledge of the stars only; information of quite a different kind, about the temperatures and chemical constitution of stellar atmospheres, has been obtained by analysing the light from the stars. From the point of view of the astronomer, the discovery of fresh facts about the stars is an absolute end in itself. Nevertheless, this information gives as a by-product information about the behaviour of the atoms, and is, surprisingly enough, ultimately of commercial importance to humanity. Airships are now filled with a gas, helium, which has the advantage over hydrogen that it is not inflammable; this gas was first discovered in the sun, but it is now found occurring in natural gases leaking from the earth; and a large number of technical devices, including valves used in wireless sets, owe their existence to the development of the science of physical optics, to which astrophysics can make striking contributions. The surfaces of the stars are far hotter than any terrestrial furnace, and in studying the light which they radiate

we study the behaviour of matter under conditions which can never be obtained in the laboratory.

The nearest star is the sun, and that is ninety-two million miles away. The other stars are very much farther off, but we can determine fairly easily within certain limits the temperatures of these remote objects, because the radiation which they send has a composition which is dependent upon the temperature of the place from which it came; and by comparing the stellar radiation with the radiation of incandescent objects in the laboratory, we can apply the laws of physics, as they are known on earth, to deduce the temperatures of these very distant bodies. The principle which we use is quite simple; a body at a certain temperature is red hot, and glows with a dull red radiation that can be seen in a darkened room (in contradistinction to a *red-painted* object which cannot be seen at all in the dark); and at higher temperatures, when the body is white hot, the light which it emits is firstly very much brighter and secondly no longer red in appearance. There is a continuous gradation both of intrinsic brightness and of colouring, and both depend on the temperature of the emitting source. The laws connecting colour with temperature can be determined in the laboratory, and when applied to the star light they will tell us the temperature of the surface of the star from which the light came.

Here let us make a digression on the colour of things in general. The key to the understanding of colour is the experiment performed by Sir Isaac Newton, who sent a beam of sunlight, which came through a hole in the window shutter, through a small glass prism (fig. 13). After passing through the prism the light fell on a

screen; it was no longer white, but had been broken up into the colours of the rainbow. We call the arrangement of colours produced when white light passes through a prism the *spectrum* of white light. Now white light is composite; it is a mixture of an infinite gradation of colours from a deep red, passing through light red, yellow, green, light blue and dark blue to violet. The proportions in which the colours occur in sunlight determine our idea of white light. A hot solid body emits all the colours, but unless the temperature is

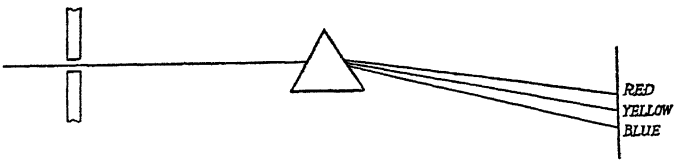


Fig 13.—Newton's experiment. Sunlight was admitted into a darkened room through a hole in a shutter. After passing through a glass prism the light fell on a screen. Newton found that the prism separated the white light into the colours of the spectrum.

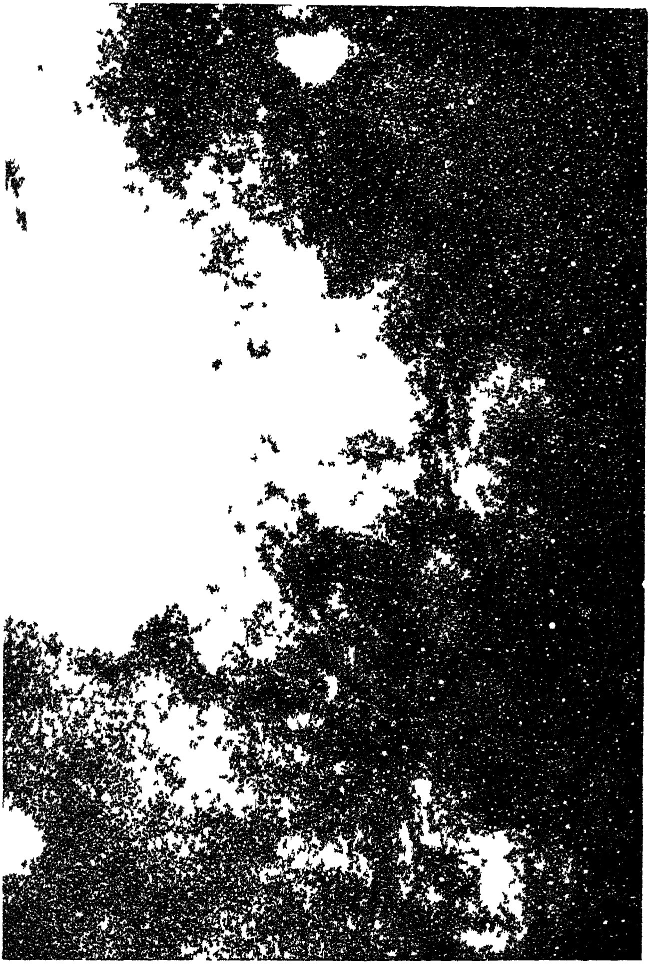
that of the sun—about six thousand degrees on the Centigrade scale—the proportions of the different colours will not be the same as those which occur in sunlight. The light coming from a red-hot body appears red because there is hardly any blue at all; the light coming from an electric light, which is a filament of tungsten wire kept at a temperature greater than red heat but less than six thousand degrees, contains a good deal of yellow light and some blue, but not nearly so much blue light in proportion to the red as sunlight does. Electric light is not quite white light, which is why one cannot match materials under electric light and be satisfied with the result next day. The colours of things fall into three classes: ordinary things about

the room are coloured by pigment, they are invisible in the dark, and are only seen by reflected light from some outside source. They appear coloured because the pigments absorb some colours out of the white light which is shone on them and reflect others. A blue dress looks blue because the dye suppresses the red and yellow light and sends back the blue to our eyes. Coloured things in the next class are self-luminous bodies which show a preference for a particular colour or colours and make no attempt to produce white light. Flames fall into this class, and so do neon signs. Throw a little common salt on the fire; you will see a characteristic yellow flame, favoured by the sodium chloride molecule. The red and green colours exhibited by the neon tubes are only too well known. In the last class are the so called black bodies, or perfect radiators, which favour no colour in particular over the others, when heated, the black bodies send out all colours in proportions which are regulated solely by the temperature of the emitting source.

When the laws of radiation were first investigated the earliest workers measured the radiation from blackened copper spheres, assuming that these objects approximated more or less closely to perfect radiators. Some years afterwards the mathematical notion of a perfect radiator was developed and its emission was calculated for all temperatures. The test of whether a particular object is or is not a perfect radiator is simply whether the radiation which it actually emits is the same as that given by the mathematical formula for the theoretical perfect radiator. The theoretically perfect radiator is called a black body even if it is white hot, the name having been carried over from

N

W



E

E 846

PART OF THE MILKY WAY
(Star Cloud in Sagittarius)

From a photograph by Franklin Adams, July 29, 1910

the early experiments on blackened copper spheres. As the M.P. said to Matthew Arnold: "That a thing should be an anomaly is no objection to it whatsoever."

Having set up a theoretical idea of a black body, it becomes necessary to ask whether anything in nature behaves in this ideal way. A thing which appears black at ordinary temperatures, such as a lump of coal or a black billiard ball is not necessarily a black body when it is heated. (It is black when it is cold simply because it quenches all the light which falls upon it, without preference for one colour over another.) We do know something which is a black body when it is heated, and that is the interior of a furnace seen through a small window. If one throws a large lump of salt into the interior of a furnace you would not see the characteristic blue colour; the salt looks red hot like its surroundings. Inside an enclosure the emission of light by the salt is dominated by the radiation all round it. It is only when it gets out in the open, on the edge of a coal fire or in a Bunsen flame, that it gets a chance to decide what colour to emit.

We can sum up this discussion by saying that if we find a self-luminous body and know that it is emitting a fair proportion of all colours, exhibiting special preference for none, or, in technical language, behaving like a black body (or perfect radiator), we can determine the temperature of this source from the proportions in which the different colours occur in the spectrum of the radiation.

The stars do behave more or less like black bodies. We have not got a great deal of evidence to show that they are indeed black bodies, except in the case

of the sun; but what evidence there is goes to support the statement that the stars have no marked preferences for the blue over the red or otherwise. Their temperatures are found from their colours by supposing that they *are* black bodies, and the temperature found in this way is called the colour-temperature. There is one simple check that we can apply: from the proportion of blue radiation to red radiation we find a temperature; does the ratio of yellow radiation to blue radiation fit in with this temperature? If it did not, of course, the star could not possibly be a black body. This check does, in fact, work properly on actual stars, but it does not necessarily prove that they are actually radiating like black bodies.

The fundamental method of determining a star's temperature from its radiation is called the spectrophotometric method. In its essentials, the method is simple enough; light from a star is made to fall on a prism, which breaks it up into a spectrum. This spectrum is focused on to a photographic plate by a camera. On the same photographic plate is photographed the spectrum of an artificial source of light—a lamp—which burns at a known temperature. The ratio of the red light to the blue light, in each case at a particular point in the spectrum, which is to say at a precise shade of colour, is found from the extent to which the light concerned has affected the plate; and from the two ratios we can calculate the temperature of the star if the temperature of the terrestrial standard is known.

Now there is considerable difficulty in getting a big prism, and the light which falls from a single star on to a small prism is not very great; so that to get any

kind of a photograph with as little as an hour's exposure it is necessary to collect much more starlight. This is where the telescope comes in. The telescope actually used in this work at Greenwich has a mirror which is 36 inches in diameter. It is a concave mirror, like the reflector behind a car's headlights, only less sharply curved; and when its axis is pointed towards a particular star, all the light which falls on the mirror is reflected to one point—the focus of the great mirror. The amount of starlight collected in this way is quite considerable. The prism is not placed exactly at this point for the technical reason that the beams passing through the prism must be parallel to one another. (This is arranged by using a second curved mirror.) But the prism and camera are both bolted to the telescope and all the light which falls on the great mirror is sent through the prism and its spectrum is photographed, and compared with the spectrum of a terrestrial source of light burning at a known temperature (fig. 14).

In this way the temperatures of a number of the brighter stars have been determined. Once a number of standard stars have been done, the work of extending the knowledge of stellar temperatures can be carried on by less fundamental but more rapid methods. For example, we can photograph a whole field of stars first through a red filter, and then through a blue filter. (The filter is just like a filter used in ordinary photography, which is to say, a film of gelatine stained with a particular dye kept between two glass covers which fit over the camera lens.) The hotter stars will appear relatively brighter through the blue filter than through the red.

The results which have been obtained show that

there is a great range in the surface temperatures of the stars. Here are some results for some well-known stars.

Vega	..	18,000°
Sirius	..	14,000°
The Sun	..	6,500°
Capella	..	5,800°
Arcturus	..	4,300°

Compare these with the temperature of an electric light filament—about 2800°; and with a red-hot coal fire, at about 1000°.

The colour difference between Vega and Arcturus can be seen with the naked eye on a very clear night in the late summer and early autumn, when Vega is directly overhead in the early evening and Arcturus, which looks as if it were a continuation of the handle of the Plough, is high in the western sky. Vega is noticeably blue and Arcturus is red.

We have skated over one of the chief difficulties, which is the behaviour of the earth's atmosphere. The sun looks very red at sunrise and sunset. So does the moon, at moonrise and moonset, if you look for it. One can sometimes see Venus looking pretty red when it gets low down, if there is no "sunset" in the sky to compare it with. The reason for this redness of setting objects is the red colour of air! We see setting objects through a very long air path, much longer than when they are overhead. All along the way the molecules in the air scatter the blue light and leave the red, not quite untouched, but far less affected than the blue. We see blue sky because we are seeing the blue light which would have landed somewhere else if it had gone on straight in its path

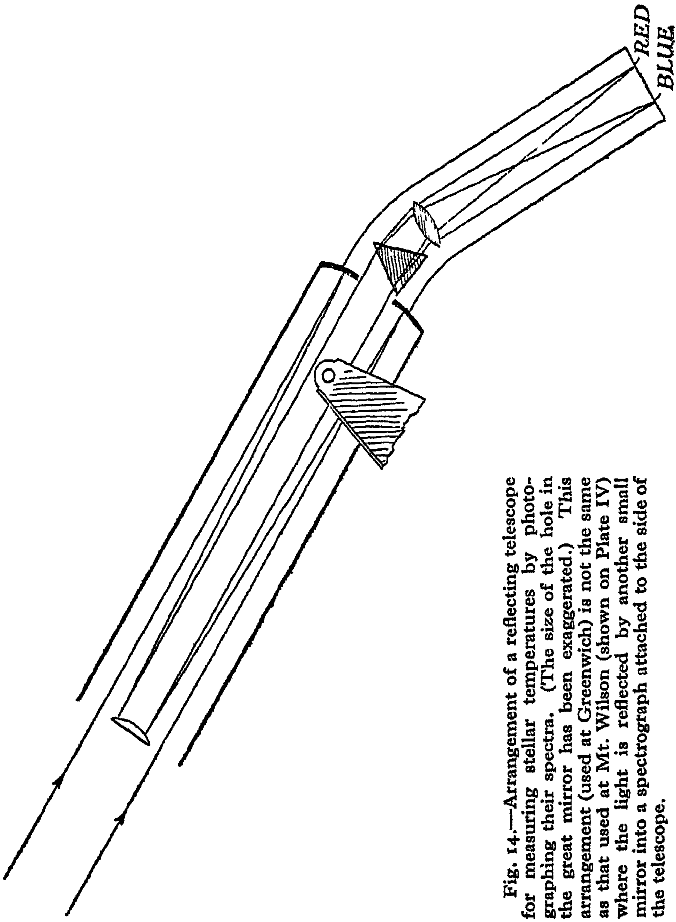


Fig. 14.—Arrangement of a reflecting telescope for measuring stellar temperatures by photographing their spectra. (The size of the hole in the great mirror has been exaggerated.) This arrangement (used at Greenwich) is not the same as that used at Mt. Wilson (shown on Plate IV) where the light is reflected by another small mirror into a spectrograph attached to the side of the telescope.

from the sun. This reddening of the direct light is most marked at sunset, but it is there all the time even at midday; if you could get outside the atmosphere you would see a slightly bluish sun compared with even the midday sun at the earth's surface. We have to make some allowance for this, and we apply a correction to the colour of the object seen on earth to correct it to the colour as it would appear to an observer outside the atmosphere. This correction is found by measuring the reddening as it goes on from midday to sunset which enables us to calculate the amount of the reddening at midday.

We mentioned before that the hotter the furnace, not only the whiter the light that comes from it, but also the more intense. And, of course, the bigger the furnace the more heat comes from it. Now we do not know the sizes of the stars (their radii, to be precise) with sufficient accuracy to find out their temperatures, but we do know the size of the sun, and we can measure directly the amount of heat which comes from it. This has been done, and the temperature of the sun has been found in this way also. The method is very pretty and in its outlines extremely simple.

Heat is measured by its capacity to heat water. The unit of heat called a calorie is the amount of heat necessary to raise a gramme of water through a degree Centigrade. In civil life in Great Britain where we stick to the pound as our unit of weight and to the degree Fahrenheit (which is five-ninths of the degree Centigrade) the unit of heat is the Therm, familiar even to those who make no use of gas through a well-known series of advertisements, which heats 1000 lb. of water through 100 degrees Fahrenheit.

Of course not all the heat from the sun falls on the earth; but we can easily reckon up the total amount of heat given out by the sun if we measure the amount which falls on one square centimetre of the earth's surface.

Imagine a sphere described with the sun at its centre with a radius equal to the mean radius of the earth's orbit, or 149,500,000 kilometres. This sphere has a surface area of twenty-eight hundred million million million million (written 28×10^{26}) square centimetres. The total heat sent out by the sun is 28×10^{26} times the amount which falls on one square centimetre. This we measure by setting up in the sunshine a little copper box with a face which is just one square centimetre in area. This face is blackened so that all the solar heat which falls upon it is retained. A steady stream of water is passed slowly through the box, and as it goes through it is gently heated by the sunshine falling on the blackened face. Thermometers measure the temperature of the water before it enters the box and after it leaves it, and the solar radiation on one square centimetre in one second is equal to the rise in temperature of the water multiplied by the weight of water which passes through the box in a second. It is found that two calories fall on a square centimetre every minute; so that the whole sun emits 56×10^{26} calories, every minute.

Of course, in finding out this result, we are up against our old difficulty that not all the heat gets to the surface of the earth because the atmosphere dissipates some of it and sends it back into space. The difficulty is overcome in the same way, by making an estimate of how much heat one kilometre of the

atmosphere removes, which is done by making measurements of the radiation received when the sun is at different heights in the sky. (This estimate has to be made separately for each colour of the sunlight and the results added together.) The observers took the further precaution of carrying the instruments up to the top of a very high mountain, Mount Whitney, the highest peak in the U.S.A., so as to get above as much of the atmosphere as possible.

Now, if you know how large a furnace is, and if you know how much heat it sends out in a second, you know how hot it is. Applying the mathematical law which embodies the precise formulation of this statement to the total amount of solar radiations, we find that the sun's surface temperature is 5740°, a little lower than the colour temperature. The sun is accordingly not quite a perfect radiator, or perfect "black body", but it is something like one.

Since the stellar diameters are unknown, we could not apply this method to find their temperatures; but if we assume that we know their temperatures from the colour temperature work we can work backwards and find the diameters. We have not yet said how so small a quantity as the heat from a star is measured. The method used for sunshine will not do; the rise of temperature of the water in the copper box would be minute. There are, however, two types of instruments which measure tiny amounts of radiant heat; these are called thermocouples and radiometers. If you join two dissimilar metals together (the best pair to use is antimony and bismuth) and heat the junction slightly, an electric potential is set up; it is possible to measure very tiny electric potentials

with modern devices. The thermocouple method of measurement consists in focussing light from a star on a metal junction and measuring the resulting electric potential. The radiometer is an odd instrument. A little set of vanes is set up in a glass bulb (like an electric bulb). One side of each vane is blackened; the vanes are mounted on a spindle and are free to rotate. When the contrivance is exposed to radiation the vanes go round. (There is sometimes a demonstration radiometer of this kind in a chemist's window.) When accurate measurement is wanted the vanes are not allowed to go right round, their movement is impeded by the torsion of a quartz fibre. We can measure the force with which the vanes twist the fibre, and very tiny forces are so measured; the force is proportional to the amount of radiation which comes from the star. When using either thermocouple or radiometer, the instrument is mounted at the focus of a great telescope, so that all the radiation falling on the great mirror can be brought to bear on the sensitive device. It is said that the equipment at Mount Wilson, California, could measure the heat of a candle on the banks of the Mississippi, more than a thousand miles away.

The stars are a long way off; so much so that although many of them are very much larger than the sun, even the largest telescope that we possess—the 100-inch reflector at Mount Wilson—will not show them as anything but points of light. But we can work backwards from temperatures, found from the stellar colours, the heat they give out, measured on a radiometer, and the parallax, measured as described in Chapter III, to find out the radii. If you know the

temperature of a furnace and its distance, and measure the heat from it, you can tell how big a furnace it is. The radii are, in some cases, very large, even compared with the sun, a respectable body whose radius is 432,000 miles. Arcturus's radius is 27 times that of the sun; Aldebaran 38 times; Betelgeuse, about 300 times; and Antares has a radius of no less than 450 solar radii. Either of the last mentioned, if placed with their centres where the sun is now, would extend right out far beyond the earth's orbit. But they are so far off that the greatest angular diameter—that of Betelgeuse—is only five hundredths of a second of arc, so that it looks to us about as large as a penny stuck on the dome of St. Paul's would appear to an observer in Oxford. This smallness defies even a hundred-inch telescope. The obstacle to magnification of a very small object is bound up with the wave nature of light. But the wave phenomena which form this barrier to direct telescopic vision have themselves provided a means of measuring stellar radii with an instrument called an interferometer, which was perfected in 1920, long after the radii had been predicted by the method sketched above. The measured radii furnished a brilliant confirmation of the reasoning; they were, within the limits of accuracy with which the interferometer could measure them, just what it was argued that they must be.

CHAPTER V

The Composition of the Stars

IF Newton had allowed the sunlight which fell on his prism to enter the room through a narrow slit instead of through a circular hole in the shutter of his window, he might have detected a remarkable thing: the solar spectrum crossed by a number of dark lines. These lines were first seen by Wollaston (1802), but they are generally called the Fraunhofer lines, although Fraunhofer did not discover them until 1814. When light from a circular hole is passed through a prism a circular image is formed in each gradation of colour, and the circular images from successive colours overlap, so that the fine dark lines, which are gaps between neighbouring colours, are blotted out. When a slit is used, on the other hand, each colour appears very nearly pure, and one sees the dark lines which were supposed by Fraunhofer to be natural divisions between different colours—but they are more interesting than that. When we talk about a particular colour we identify the precise colour by the amount that the ray is bent in passing through a prism. According to the wave theory of light, a particular colour is a particular wavelength of light, and a particular frequency of the vibration; but it is enough in the present connexion that the particular wavelength, or

particular colour, can be identified by some means. It was found that the dark lines in the solar spectrum coincided exactly in wavelength with bright lines in the emission spectra of certain terrestrial elements. For example, if a little common salt in solution in water is introduced into a Bunsen burner by dipping a bit of asbestos in the solution and thrusting it into the flame, a brilliant yellow colour appears. If light from this yellow flame is passed through a prism and then examined, it is found to consist of two wavelengths only, very close together, in the yellow region of the spectrum. Two dark lines occur at exactly the same wavelengths in the solar spectrum. It was rightly supposed that if the sodium in the common salt selects these two wavelengths for the emission of its flame spectrum, it is sodium that obstructs the light coming out of the sun in these two particular wavelengths and causes the appearance of the dark, or absorption, lines in the solar spectrum. The absorption can be demonstrated in the laboratory by setting up a bright white light behind a sodium flame; the spectrum of the combination shows dark lines where the bright yellow lines are seen from the flame alone. It is part of a very general principle that if a substance selects particular wavelengths for emission, it will select the same wavelengths for absorption. These two Fraunhofer lines, then, tell us a very interesting thing, that there is sodium on the sun. There are altogether thousands of Fraunhofer lines, and they have been catalogued according to their wavelengths, and a comparison has been made between the wavelengths of the Fraunhofer lines and all the wavelengths in the spectra of the terrestrial elements. Nearly all

of the strong Fraunhofer lines have been identified with bright lines emitted in the laboratory by terrestrial elements; a few strong lines and many weak ones have defied identification up to the present date. The two strongest lines in the solar spectrum have been identified with calcium; next in strength come a family of lines due to the absorption of light by hydrogen. Amongst the other elements iron is most conspicuously represented, there being literally hundreds of iron lines scattered all over the spectrum from red to blue.

Not all the elements known on the earth are represented in the solar spectrum. For example, no lines due to gold, silver or mercury have been detected, but this does not necessarily mean that these elements are not to be found at all in the sun. We only see the surface, and these elements are heavy. It is not believed that there are any elements on the sun which do not occur on the earth; but in the early days of spectroscopy, certain solar lines were identified, provisionally, with an unknown element which was called *helium* from the Greek ἥλιος sun. Some time later when a hitherto unknown gas was discovered on the earth, it was found to exhibit bright lines which correspond exactly to the helium lines on the sun, and the terrestrial gas is now called helium. Although some other unidentified lines were at one time assigned to hypothetical elements, called coronium and nebulium because the lines were observed in the solar corona and in the nebulæ respectively, it is not now supposed that there *are* any unknown elements—at any rate, any elements lighter than the heaviest found on earth (uranium). We think this because a great Russian

chemist called Mendelieff arranged the chemical elements in order of increasing atomic weight and showed that every ninth element reproduced in a striking way the properties of the first. In order to exhibit this arrangement, Mendelieff had to leave gaps in the table which were to be filled by elements then undiscovered. He went so far as to predict what the characteristics of the elements would be when they were ultimately isolated. This was in 1870. We have now found more chemical elements and filled all the gaps in Mendelieff's table, and his predictions have been fulfilled; and we do not suppose that any more chemical elements remain to be found, notwithstanding the unidentified lines in the sun, which we suppose are emitted by terrestrial atoms under solar conditions. The reason why we have not yet succeeded in reproducing in terrestrial laboratories all the lines seen in the sun is that it is impossible to produce the very high temperature on the sun. The atom requires to be subjected to great heat before it will show certain lines.

The modern practice in observing spectra differs from Newton's simple arrangement in certain particulars. To begin with a slit is nearly always used; and it is usual to employ a large lens, called the object glass, to concentrate the sunlight on the slit, in order to get enough light to give a good bright spectrum. It is necessary to make the beams of light parallel when they go through the prism (so that they will receive equal refractions) and for this purpose a second lens, the "collimating" lens, is used. Finally, after passing through the prism the rays are focussed by a third lens, the camera lens, into an eyepiece or on to a photographic plate (fig. 15). In some cases a battery of prisms

is used to get greater dispersion than can be obtained with one prism alone.

The whole apparatus could be strapped to a telescope and made to follow the position of the sun by clockwork, but a more convenient arrangement is generally used, which permits of the spectrograph being kept stationary. This is the heliostat, which is a mirror driven by clockwork in such a way that it always reflects the sunlight in the same direction. The light

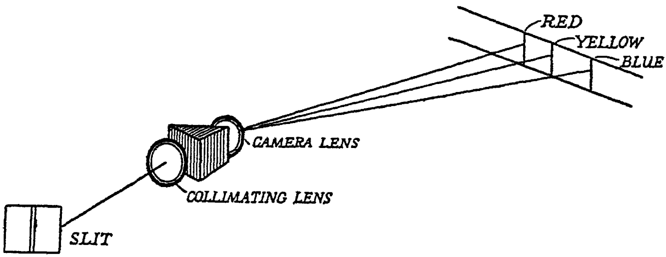


Fig. 15.—Arrangement of a Spectrograph

is then reflected on to a stationary object glass by a second mirror. Behind the object glass stands the spectrograph, which may be a very bulky thing, and is kept for choice at a constant temperature. Perhaps the best instrument for studying the solar spectrum—it is certainly the largest—is the 150 feet solar tower at Mount Wilson. The heliostat M_1 is placed on top of a tower 150 feet high, and the secondary mirror M_2 reflects the beam vertically downwards on to an object glass L_1 which brings the rays to a focus on the ground level, where the observer works. The spectrograph is housed in a pit 75 feet deep, the slit S being at ground level. The rays go down to a collimating lens L_2 which is also the camera lens; after going through the prism (or its

equivalent, the diffraction grating) the rays are sent back again to the ground level where they can be observed or photographed (fig. 16).

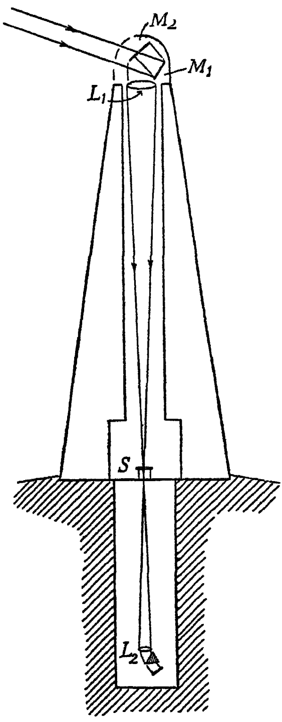


Fig. 16

Striking features of the sun's surface are brought to light by photographing it in light of a particular wavelength only. This can be done by placing a narrow slit just in front of the photographic plate; the plate then photographs in a particular wavelength a narrow strip of the sun—that strip, which is projected through the first slit by the object glass. By driving the two slits along together with an electric motor one builds up, step by step, the whole image of the sun in the particular wavelength which the second slit is adjusted to receive. An image of the sun built up in this way is called a spectroheliogram. They are usually taken in calcium light or in hydrogen light. On some days nothing unusual is seen beyond the ordinary granulation on the sun's disc, but on other occasions, particularly during periods of great sunspot activity, very bright patches can be seen on the solar disc, as well as characteristic dark markings. Further, the prominences can be photographed in this

way, even when there is no eclipse of the sun. The glare which ordinarily hides the prominences is mixed light, and does not contain much hydrogen wavelength light. Since the spectroheliograph selects only the hydrogen wavelength it turns aside most of the glare and reveals the prominences. The prominences show up well in both hydrogen and calcium light, and therefore contain both these elements.

If any source of light is in an intense magnetic field the lines in the spectrum of this source will show a certain disturbance characteristic of the strength of the magnetic field. It is found that the light coming from the sunspots shows this magnetic characteristic; the sunspots are accordingly known to be seats of intense electromagnetic disturbance. This disturbance is so great that sunspots are connected, in some degree at least, with magnetic storms on the earth. The reader has lived through many magnetic storms without in the least being aware of their existence, unless he observed at the time a delicately balanced compass needle. Magnetic storms do not produce thunderstorms or any other striking meteorological phenomena, except the aurora borealis or northern lights—seldom seen in England.

The spectral lines tell us another very important characteristic of the source from which they come—its velocity towards us, or away from us. This indication of velocity is called the Doppler effect. Sound shows the same effect, and railway engines sometimes give a very good illustration of it. If an engine whistles when passing rapidly by a platform on which one is standing one can detect an apparent change in the pitch of the whistle, which drops through a semitone or two as

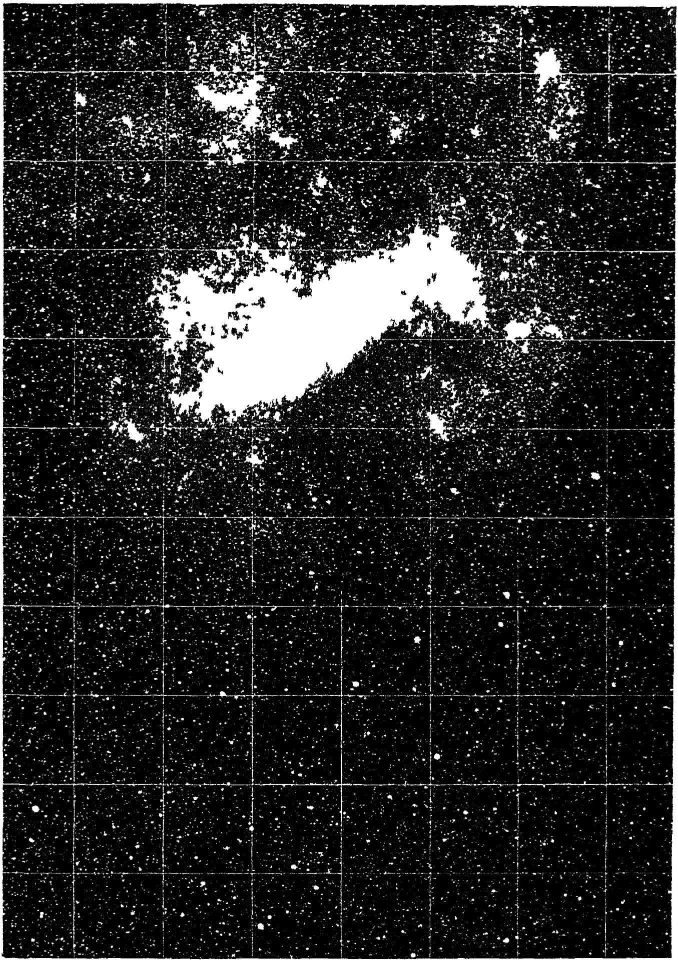
the engine goes by. When the engine is approaching the listener the pitch appears sharper than that of the stationary whistle, and when the engine recedes the whistle sounds flat, the alteration in the pitch depending in both cases on the speed of the engine. It is so with light. Colour in light corresponds to pitch in sound, and a source coming towards a spectrograph shows lines displaced to the violet, and a receding source shows lines displaced to the red, the displacement being an accurate measure of the velocity of recession or approach. These Doppler effects can be seen in the solar spectrum; opposite edges of the sun, the east and west limbs, show opposite Doppler shifts, showing that the sun is rotating. The bright and dark hydrogen patches show very striking Doppler effects; velocities as high as 1500 kilometres per second (about 1000 miles *per second*) have been recorded. Some of these clouds are very short-lived, and only persist for twenty minutes. They are great jets of hydrogen which spurt out of the sun with this incredible velocity, and either melt away or fall back again. The sun's surface is, at times, full of incident.

The spectrograph has been turned on the stars. The problem of securing stellar spectrograms is very different from that of obtaining spectrograms of sunlight. There is plenty of light from the sun; so much that with a twelve inch objective one can expose a spectrogram with very high dispersion—that is to say, spreading out the spectrum over a large area, so that the details of fine lines situated very close together in wavelength can be easily seen—in a matter of five seconds or so. But the light from the brightest star is so feeble in comparison with the sunlight that as

large a light grasp as possible is used, and the dispersion is much more modest, and even then it will take several minutes to expose the spectrogram on bright stars. An enormous wealth of detailed information about stellar spectra has been secured. Stellar spectra are classified according to an odd system of nomenclature. The hottest stars are classed in type O, and the coolest in type N, the sequence being O, B, A, F, G, K, M, R, N —which one can best remember with the help of the mnemonic, "Oh be a fine girl, kiss me right now". Stars in the so-called early types O, B and A exhibit few lines, chiefly the lines due to hydrogen. The brightest B stars are Rigel, Spica and Regulus, and the brightest A's are Sirius and Vega. As we progress down the series the hydrogen lines become weaker and the metallic lines increase in strength. F type stars, such as Canopus and Procyon show some metallic absorption. The sun is a G type star, showing strong hydrogen lines (though much weaker than those in earlier types), and in addition a considerable amount of metallic absorption. In the K and M type stars the hydrogen absorption has disappeared and the metallic absorption has become very heavy. Typical K stars are Arcturus and Aldebaran, and Betelgeuse is in class M. In the R and N types molecular spectra of hydrocarbons and cyanogen appear. The earlier type stars are so hot that they *dissociate* the molecules into their constituent atoms. Cyanogen is a chemical compound, the molecule of cyanogen consisting of an aggregation of carbon and nitrogen atoms. The hotter a substance becomes the more violently are its molecules agitated and the thermal agitation tends to break up these aggregations of atoms into single atoms; cyanogen

breaks down into carbon and nitrogen. Few compounds can exist on the sun. There are very feeble traces of cyanogen in the solar spectrum, and rather stronger lines in the spectra of sunspots, which are cooler than the rest of the disc, so that the atoms have more chance to cling together and form the compound. The spectrum of any compound is quite different from that of its constituents, the presence of a partner quite upsetting the atom's modes of vibration. An example is afforded by common salt. Thrown into a fire the salt shows a *blue* flame due to the vibrations of the molecule of sodium chloride; but if one dissolves the salt in water the molecules dissociate into their constituent atoms, and the conspicuous *yellow* colour given out by sodium alone is exhibited by a salt solution thrust into a flame. There is enough salt in ordinary tap water to show the yellow flame when a kettle spills over on to a gas ring.

A laboratory study of spectra shows that the type of spectrum which a given atom emits depends very largely on the circumstances in which it is made to emit the radiation. There are, broadly speaking, three stages of agitation to which physicists can subject atoms in the laboratory. The mildest treatment consists of heating the substance in a furnace; the next stage consists in introducing some of the substance into an electric arc. Electric arcs are made by sending a direct current across a short air gap (a quarter of an inch or so) between terminals made of the material. If one passes a heavy electric current through two iron nails which just touch each other and then draws the nails apart the current will jump across the gap, being carried by the white hot particles in a cloud of vaporized



E 846

LARGE MAGELLANIC CLOUD

From a photograph taken at the Cape of Good Hope by
Franklin Adams, November 15, 1903

Facing p 100

iron. The arc sends out a very intense light which exhibits a spectrum characteristic of the material of which the poles are made, so that if the poles are iron nails we shall see the iron arc spectrum. The third stage of agitation to which we subject atoms is the electric spark. If one applies a high voltage *alternating* electric force to an air gap it will send a spark across the gap. The light is not so intense as the arc, but the agitation of the iron particles is more violent in the spark than in the arc, and the spark spectrum, which is again characteristic of the material of which the terminals are made, is quite different from the furnace spectrum of the element, the arc spectrum being between the two, and containing both furnace lines and spark lines. If one could make a hot enough furnace it would show the enhanced (spark) lines, but it is technically impossible to heat up a furnace to such a point. The spectrum being characteristic of the temperature of the source we should expect the details of stellar spectra to indicate to us the surface temperatures of the stars, and it is found that furnace lines are very strong in types K and M and that the enhanced lines begin to appear in type G. The F type stars show the enhanced lines very strongly. Type A shows most strongly the hydrogen lines which are spark lines, and the two hottest types of stars show lines which are difficult to produce at all in the laboratory. The temperatures of the stars given by the study of their spectra fit in very well with the colour temperatures, and the spectral sequence is also the sequence of descending colour temperature. We have two absolutely distinct lines of argument in favour of the assertion that the surface of Vega is very much hotter

than that of the sun, which is again hotter than the surface of Arcturus.

Stellar spectra show well marked Doppler effects. Despite their apparent fixedness, the stars are moving about; this, of course, can be seen in their proper motions. Proper motion indicates apparent motion, and cannot be converted into actual velocity in kilometres per second unless the star's distance is known, but the radial velocities shown by the Doppler effect are actual velocities in kilometres per second. The two motions, proper motion and radial motion, are at right angles to one another. The spectroscope shows that certain stars are binary stars, although they are so far off that the two components cannot be separated even with the most powerful telescope. The best example is Capella. The spectrum of this star shows two sets of lines with different Doppler effects; the two Doppler velocities vary in exactly the way which corresponds to the spectra of two stars revolving round a common centre of gravity. The orbits of the two stars can be found from the Doppler shifts and their masses found in the same way as is the case for a visual binary. Capella has particular interest, because a visual orbit has been calculated for the system from interferometer measurements. We can compare the apparent orbital motion with the actual spectroscopic motion and deduce how far off the star is, much more accurately than we can find out by the ordinary parallax method.

The assumption that Algol is an eclipsing binary has received confirmation from spectroscopic observations, the spectrum being in fact that of a binary having the same period as the period of eclipse. This

spectroscopic confirmation has been obtained in every Algol-like variable star; the Algol variables, it will be remembered, are those in which the magnitude remains constant except at the definite times of eclipse.

The stars can be classified in two ways, as we have seen; they can be classified in order of absolute magnitude, and they can also be classified according to the spectral sequence, or according to colour temperature, the last two methods coming to much the same thing, being different methods of classifying them according to surface temperature. If the stars were all the same size, absolute magnitude would also depend only on temperature; and if the size depended on the temperature we would expect to find some correlation. For example, the stars with the highest temperatures might be the biggest stars; but this is not found to be the case. The B type stars are a fairly uniform collection, and have absolute magnitudes ranging from -5 to 0. The A's, F's and G's are progressively fainter than the B's, the average G type star having an absolute magnitude between $+2{\cdot}5$ and $+5$. While most of the K's and M's continue this sequence, giving the typical M star an absolute magnitude of $+10$—so that it emits about a hundredth of the light emitted by our sun, some of the K's and M's are as bright as the brightest B stars—giving out a million times as much light as the faint members of the same spectral type. The division into giant and dwarf K and M type stars is fairly complete. There is no bourgeois, middle-class M type star like the sun. The M star is, in luminosity, either an aristocrat, or a serf. Outside the ordinary division into giants and dwarfs there are a few very bright stars, such as Rigel, type B, α Cygni

type A, and Canopus, type F, which are distinctly brighter than even the giants. These are sometimes called super-giants.

Giant stars are not so common as dwarfs in the region near the sun, but they tend to gain an unfair representation in any set of stars including all those down to a given apparent magnitude—as, for example, in a list of naked eye stars, or a list of stars that can be seen with a particular telescope, because giant stars can be seen when they are much farther away than dwarfs. For example, you cannot see an M type dwarf ten parsecs away with the naked eye, because its apparent magnitude is $+10$; but an M type giant at the same distance would appear as bright as Sirius. Arcturus, Aldebaran, and Betelgeuse are all giants of late type. Their great absolute magnitudes are not due to their great heat, as stellar heats go, for they are all cooler than the sun; they look as bright as they do simply because they are enormous bodies, in comparison with the sun.

An interesting example of the types of reasoning that astronomers apply to the stars is afforded by Sirius—especially as the reasoning led in this case to very startling results. Sirius is a double star. The two stars are very unequal in brightness. Sirius A is the brightest star in the sky, but Sirius *comes* is very faint—a hundred times too faint to be seen with the naked eye, even if the eye was not dazzled by the bright companion. The two stars are, however, apparently separated by seven seconds of arc when farthest apart, a quantity that can very easily be resolved by a good telescope, and the apparent orbits of both stars can be found in the usual way. Since

the system is only three parsecs away, the parallax is well determined, and the actual orbits can easily be constructed. The maximum separation is twenty times the radius of the earth's orbit. From the application of Newtonian law to the two orbits, which are described in fifty years, we find the masses of the stars, which turn out to be not very unequal; Sirius A has two and a half times the sun's mass, and Sirius *comes* is almost exactly equal to the sun in mass. The question then arises, how is it that the companion is so much fainter than the primary, if they are not very different in mass? Sirius A is known to be pretty hot, even as stars go. Its spectrum is of type A and its surface temperature accordingly is about 12,000°—nearly twice the temperature of the sun. From the apparent magnitude and known distance of both components we can deduce their absolute magnitudes—the actual amounts of light that they send out. Sirius A sends out twenty-six times as much light as our sun, and the companion sends out only three thousandths of the amount of light that the sun emits. Now, if Sirius *comes* was very much cooler than Sirius A, it would send out much less light even if both were the same size; for example, if the companion was an M type star with a temperature of 3000° it would send out $\frac{1}{256}$ of the light sent out by the bright star, area for area, so that it would have to have one-sixth of the radius of the bright star (that it would present one thirty-sixth of the surface area) in order to send out the observed proportion of light. In this there would be nothing unusual, and it was generally supposed that *comes*, being so faint, must be an M type star. Surprise was considerable, then, when the spectrum was first

photographed and was found to be of type F, so that the surface temperature of Sirius *comes* is about 8000°, sending out about one-fifth as much light, area for area, as the bright star. Since the whole surface of the companion only succeeds in emitting $\frac{1}{78000}$ of the amount of light that is sent out by Sirius A, the companion must have a very tiny surface area—in fact, it can only have a radius of twelve thousand miles, rather less than that of the planet Uranus. Yet the companion is as massive as the sun! Since so great a mass is compressed in so tiny a bulk the density of the matter in this star is about *one ton per cubic inch*—sixty-one thousand times the density of water, and three thousand times the density of anything known on the earth.

At one time it was thought that there must be some flaw in the chain of reasoning which led to so extraordinary a result; but modern ideas on the nature of the atom lend support to the possibility of ordinary matter attaining this very great density, under exceptional conditions. Atoms are conceived to consist of very minute nuclei carrying a positive charge of electricity, round which electrons travel in elliptical orbits like planets round a sun; the atom as a whole derives its volume from the presence of these outer electrons, the space between electrons and nucleus being empty. There is nothing very solid about matter to a body so small as an electron, and when our physicists fire an electron moving fast enough at a solid obstruction—like a thick steel plate—the electron stands a good chance of going right through, leaving the steel plate absolutely unpunctured—just as one might fire a rifle bullet through an open grove

of trees. The atoms, then, being such open-work structures, they can conceivably be packed much closer together if the outermost layers of electrons have been stripped off; and this is what has happened in Sirius *comes*. No physicist has yet solved the technical difficulties involved in stripping electrons off atoms and packing the atoms so tightly that he could deliver to you a matchbox weighing a couple of tons (perhaps this is well, as the dense matter is very highly electrified, and when you opened the matchbox there would be the most violent explosion).

These very tiny, very dense stars are called White Dwarfs. They are, of course, hard to see, being so faint; and until the parallax is determined, they are mistaken for ordinary F type stars, looking faint just because they are a long way off. A few others have, however, been detected in addition to the companion to Sirius.

At the other end of the density scale are the giant late type stars like Betelgeuse. Although Betelgeuse has a diameter three hundred times that of our sun—so that if substituted for the sun it would stretch out beyond the earth's orbit—it is not particularly massive, being only fifteen times as massive as the sun. Its density is accordingly only about a millionth of the density of water, or a thousandth of that of the air we breathe. Betelgeuse is as rarefied as a *vacuum* of an imperfect character. If one could send a salamandrous emissary to bring back a bucketful of Betelgeuse in an airtight asbestos-lined tin, the heat from it would not boil a cupful of water.

The pyrheliometer measurements of solar radiation, described on p. 87, show that the sun is radiating

energy at such a rate that even at this distance of 92,900,000 miles from the centre, every square centimetre receives two gramme calories per minute. Add up the number of square centimetres in the surface of a sphere of radius, 92,900,000 miles radius, and multiply by 2; we get the number of calories sent out by the sun in a minute. Multiply by the number of minutes in a year and we find that the sun's annual output is 2,830,000,000,000,000,000,000,000,000,000,000 calories. Nevertheless, the sun is a very massive body, and it is much hotter in the interior than at the surface. Sir Arthur Eddington estimates that as it is at present the sun contains enough heat to keep up this lavish expenditure for forty-seven million years. This may sound a long time, but it is not very long, according to geologists. The age of the earth has been estimated in a number of ways. By taking the amount of salt in the sea, and estimating the rate at which rivers are depositing the salt which they bring down from rocks and soil, we can divide out to get the age of the oceans; some sort of estimate can be made of the time that it must have taken to deposit the various sedimentary rocks known to geology; and, most reliable of all, from the radioactive content of rocks it is possible to calculate their age directly. In these ways the age of the earth has been estimated at a thousand million years. The sun is presumably considerably older; so that forty-seven million years' supply of heat is not very much to keep, unless the sun is not living on its capital, but is manufacturing heat as it goes. There is nothing unusual in this, of course. A coal fire manufactures heat as it goes, by burning carbon with oxygen to form carbon dioxide. But the sun

is certainly not burning like a fire—it is *too hot* to do that! We know this for certain, because there are no chemical compounds in the sun; one can tell this from an examination of the spectrum. In particular there is no carbon dioxide or water, which would be present in the form of steam in a laboratory furnace where hydrogen is burning with oxygen to form water. Even, however, if the sun was burning, and if the whole of the sun was undergoing the most violent chemical reaction known on earth, the heat that it would manufacture would be quite insufficient to prolong its life far enough back into geological time. It must manufacture heat in some other way. The great nineteenth-century physicist, Lord Kelvin, advanced the theory that the sun obtained its heat by contracting under its own weight. We know that every form of energy is equivalent to heat, and can be converted into heat. For example, the motorist has gravitational energy in his car when it is at the top of a hill. He shuts off his engine, releases the brake, and coasts downhill. He gets up speed; he has converted the gravitational energy into kinetic energy (energy of motion). Approaching a sharp bend in the road, our motorist wishes to get rid of some of his kinetic energy, so he puts on the brake, which removes some of the kinetic energy—which appears as heat in the brake bands, as many a motorist has discovered to his sorrow when the asbestos brakes start to smoke with burning oil after too liberal an application of the brake on a downhill run. But by setting his brakes on fire, the motorist illustrates Lord Kelvin's principle that decrease of gravitational energy liberates heat. A slowly collapsing sun continually liberates heat, all the particles running down-

hill at once, and being obstructed by friction against each other, the collisions generating heat. Precise calculation showed that the age of the sun, supposing the energy to be due to contraction alone was 20,000,000 years—not nearly enough, as the geologists of the time were quick to point out. The physicist no longer replies, so much the worse for geology; he agrees, instead, that contraction will not do. For one thing, if the Cepheid variables were contracting, their periods would be continually decreasing, and at least one of them, the type-star δ Cephei, has been observed long enough (since 1785) to show that its period is not decreasing nearly fast enough to agree with the contraction hypothesis; further, one of the Cepheids, η Aquilæ, is actually increasing its period.

When radioactivity was discovered, it was thought that here was a source of heat which would account for the solar output of energy. Certain atoms are found in the laboratory to be radioactive. They liberate heat spontaneously without chemical combination taking place. They cannot, of course, be making something out of nothing ("nothing for nothing, and very little for sixpence" is a cardinal principle in heat production, as in economics), and the atom is, in fact, giving up energy at the expense of its internal resources. An atom of uranium will, in some thousands of years, go through an elaborate system of changes until it becomes an atom of lead. Each change is accompanied by a loss of energy on the part of the atom and a gain of energy on the part of its surroundings. While the changes in an individual atom take place by fits and starts, some stages lasting a thousand years and some only a few hours, a lump of uranium

together with its products (of which the well-known radium is one), containing some millions of atoms, will liberate energy continuously. There is nothing essentially unworkable in the theory that radioactivity is responsible for the solar energy; but precise calculations show that even if all the sun was composed of nothing but uranium and its products in natural proportions, radioactivity would only supply half the actual solar radiation. And, of course, the sun is *not* composed entirely of uranium—it is mostly hydrogen, which is not a radioactive substance. Indeed, no trace of uranium or of lead has ever been seen in the solar spectrum.

We must look elsewhere for some sub-atomic source of energy. It was shown theoretically by Einstein that mass is equivalent to energy, so that an atom can give up energy if it can be persuaded to decrease its mass. This phenomenon (on a very tiny scale) has actually been observed in the laboratory, though the complete breakdown of an atom into nothing but energy has yet to be seen on this planet.

As might be expected, the amount of heat obtained from annihilating one gramme of matter is very considerable—enough to boil twenty million kettles, each containing ten thousand grammes of water. We have at last unearthed a way of manufacturing energy which will meet even the sun's requirements. If the source of solar energy is really the annihilation of matter—so that, like the sacred pelican of Corpus Christi, which sacrifices its blood to feed its young, the sun destroys its substance in order to shower energy on its attendant planets—then the total available store of energy is very great, being no less than the

mass of the sun converted into energy units. This works out at one and a half million millions of years' supply, at the present rate of expenditure. This is, of course, a lavish reserve, and some sub-atomic process less drastic than the total annihilation of matter will give the most tardy geologist enough time to form the world in. But whatever the nature of the sub-atomic process, it may be supposed that the sun's output of energy is at the expense of mass, even if the atom merely goes from heavy to less heavy rather than from something to nothing; in either case, we say, the sun is losing mass at the rate of 130 million million tons per year. As these things go, this is not much of a rate; a mass equal to that of the largest of Jupiter's moons would keep the sun going for a million years, and the mass of the earth would stoke the furnace for a hundred millions.

In an age thoroughly familiar with the idea of evolution, slopped over from its original province of biology into almost every conceivable sphere of human and natural activity, it is only to be expected that astronomers have looked for evolution among the stars. It is a particularly difficult thing to trace the life history of particularly long-lived objects, and the stars are the longest-lived things of all. Except for an occasional Nova, which has not as yet been found very helpful in this connexion, the stars do nothing from century to century—except the variable stars, which keep on varying. The geologist can say much the same of the natural species among animals; none of them have varied appreciably in recent times. But the geologist finds natural evolution in the fossil records that he finds in antique rocks; and there are no fossil

stars. We have to construct a star's life history from the assortment of stars as they are at present. It is generally felt that the spectral sequence is in some sense the life history of a star. Further, if the stars expend energy at the cost of decreasing their mass, the most massive stars must be the most recent and the least massive the oldest. The evolutionary scheme, or more properly, the life history of a typical star, then, seems to be something like this. The star starts off as a giant of type M, like Betelgeuse. It contracts and grows hotter, passing rapidly (for a star) up the spectral sequence to type A or B. This point of maximum surface temperature, when the star is something like Vega, is reached one aeon after the start (giving, temporarily, the name " aeon " to a hundred thousand million years). From here onwards the star declines in surface temperature, mass and luminosity, reaching the G type, like our sun, in a further fifty aeons or so. Its subsequent decay to type M is even more leisurely, and may occupy two thousand aeons. There is a suggestion that it is, at least in some cases, the final destiny of a star to become a white dwarf.

At the present time, however, it must be said that there is something of a tentative nature about our life history of the stars. There are even some difficulties, which we have not touched on, in the path of the theory that the solar energy is due to destruction of mass.

CHAPTER VI

Galaxies: Nebulæ

THE appearance of the bright stars in the heavens, as seen by the naked eye, suggests no orderly plan at all. The peculiar arrangement in constellations presents no regular pattern and no symmetrical scheme. It must be admitted that the bright stars, in the near neighbourhood of the sun (comparatively speaking) are a random arrangement. Only when we go on to consider the motions and positions of the thousands and millions of fainter stars—fainter because further off—is any orderly arrangement apparent. This evidence of order can only be obtained from a statistical, systematic study of the positions and motions of very large numbers of stars. Now there are 4,850 naked eye stars—stars, that is to say, brighter than the sixth magnitude; but there are more than two million stars brighter than the twelfth magnitude, and it is estimated that there are 1,000,000,000 stars brighter than the twentieth magnitude. The task of collecting all the information that we could get for each individual and combining the data so obtained into a grand synthesis is accordingly an immense one. Astronomical work naturally divides itself into two parts; one concerned with the invention of yet more methods of obtaining

information about special stars, and the interpretation of the data such as they are at present known about the bright stars; and the other, the endeavour to push forward by unremitting labour the task of completing our knowledge of the stars as a whole by the mass production of magnitudes, parallaxes (if obtainable), masses, spectral types, colour temperatures, and proper motions. Of all these measurements, the measurements of magnitude and proper motion can be pushed the furthest. As long ago as 1887 an International Conference of astronomers laid down plans for a scheme of International co-operation in making a catalogue of the positions of all the stars in the whole sky down to the eleventh magnitude. With this end in view the sky was parcelled out among the various observatories of the world. The work was to be done by photographing sub-sections of the sky, and the subsequent measurement of the positions of all the star images on the photographs. It was expected that the work would be completed in five or ten years; but up to date less than half of eighteen observatories have finished their sections; the first to finish were Greenwich (1908) and Oxford (1911). The war, of course, hampered the work very materially.

In the Oxford section 1180 photographic plates were taken, and from these plates the positions of 470,873 stars have been measured and catalogued; from the work that has gone on so far it is estimated that altogether four and a half million stars will have been catalogued. The catalogue when completed will tell us very little directly, but in a hundred years time it will be a very valuable document because it will tell the astronomers of the future *where the stars*

were in our time; they will, in fact, be able to get good proper motions from it—if they do the work all over again! Five hundred years hence the twentieth-century catalogue will give very good proper motions. The astronomers of A.D. 2400 will be able to measure the right ascension and declination (the celestial longitude and latitude) of any eleventh magnitude star, and look up the records to see where it was five hundred years ago: comparison will give them a reliable value of the apparent motion per century. Out of the complete investigation of all four million stars they will have an excellent opportunity to find out what order there is among the motions of the stars.

We may look for order in other respects; in spectral type, in colour, and so on. In order to systematize the attack on so great a problem as the collection of the statistics of the whole sky, the Dutch astronomer, Kapteyn, suggested the plan of *selected areas*. Astronomers have agreed to push on with the intensive examination of a limited set of special patches in the sky—dotted about impartially so as to secure a fair average sampling. In this way the fainter stars come up for examination if they happen to be in a selected area before stars a little brighter which do not happen to be in a selected area. Now this scheme helps us to get a more uniform knowledge of the stars as a whole than the more obvious scheme of attacking *all* the seventh magnitude stars first, then all the eighth, etc.; because if one examines the stars simply in order of brightness too many giants and B stars turn up; being absolutely brighter, they turn up far too often in a statistical survey which uses apparent brightness as the sole criterion of whether the stellar candidate is to be

admitted to the examination or not. Suppose that you wish to investigate the population of a river, and there are two ways of doing it; one to net all the fish above one inch in length from river mouth to source, and the other to collect *all* the fish in selected pools. Now a fish which was not examined because it was under one inch in length might be a very young salmon or a very young trout, but it might be quite a large stickleback, or even a very large tadpole; so the first method of survey would lead one to deduce an incorrect proportion of noble to ignoble fish (and amphibians) in the stream. The selected areas in the stream give a much fairer notion of the fishy population—if care is taken to get all sorts of areas, the running water as well as the stagnant.

We have to put in the reservation in the case of the sky—the proviso that all sorts of areas must be selected—because there is a very definite difference between some parts of the heavens and others. The Milky Way—which we have not yet mentioned—makes this difference. The Milky Way is a gigantic belt across the heavens in which there is a very great concentration of faint stars. It is an unmistakable object even in the befogged skies near London; it stretches from the gap between Betelgeuse and Procyon (which it nearly fills) through Auriga, Perseus and Cassiopeia, and then on to Cygnus and Aquila. It goes in a great ring round the sky from North to South, and is a very conspicuous object in the South African and Australian sky, passing through the constellation of the Southern Cross.

Telescopic examination shows that the cloudlike Milky Way is a miscellaneous aggregation of faint objects; faint stars, actual clouds of stellar gas, and

even clouds of obscuring matter—such as the conspicuous "coal sack", a black patch in the Milky Way near the Southern Cross. The Milky Way lies in a plane—more or less; this plane is called the plane of the galaxy. It is not only the faint stars that tend to group themselves near the galactic plane; O stars particularly and B stars generally tend to group themselves near it, but the naked-eye M stars are distributed impartially through space without preference for the galactic plane. The situation may be described by saying that the whole system of stars, or galaxy, is a flat, circular aggregation of stars—shaped like a biscuit, the Milky Way being the plane in which the biscuit lies. Nearby objects, such as naked eye M stars, are distributed all round us, as we are near the middle of the thickness of the biscuit, but very distant objects, such as faint B type stars, appear to us to be almost exclusively in the plane of the galaxy. Imagine an actual biscuit—a big one, with currants. To a microscopic inhabitant of the biscuit (endowed with telescopes that can see between the crumbs) crumbs will appear scattered in all directions, but the distant currants will be seen grouped about a particular plane—the plane of the biscuit.

It should be said that we are well aware of a limitation of the galaxy. If stars were distributed uniformly through space, as far as the eye (aided by the most powerful telescope) could stretch, the bigger the telescope we used, the more stars we should see, and each successive magnitude embracing still fainter stars should bring in an ever-increasing number of discoveries; but in actual fact, after a certain limit, even the M type stars begin to peter out when you look away from the

galactic plane. Our galaxy is a definite island of stars, surrounded by outer space.

The galaxy is so large that the ordinary method of parallax is powerless to deal with the measurement of it. It is not much good trying to measure an angle much smaller than one hundredth of a second of arc, and it is useless to try to measure any angle less than a thousandth of a second of arc; so that farther than a thousand parsecs, we have to rely on other methods of measuring distance. The distance to a cluster of stars a long way off can be estimated in various ways: firstly, by examining the spectral types and apparent luminosities of the stars in it—if they are still bright enough and distinct enough to have their individual spectra taken. From our examination of local stars we know that the absolute magnitudes of the G's, for example, are all round about +5 (barring an occasional giant). If then we find a cluster in which the G stars appear to have a magnitude of 15, we know that they are that distance away which makes them appear ten magnitudes fainter than corresponding stars at the standard distance of ten parsecs. Now ten magnitudes is a decrease of one ten thousandth of the amount of light, so that the cluster is the square root of ten thousand, or one hundred times the standard distance. Answer: the cluster is a thousand parsecs away. Then, again, there is the very powerful method of examining the cloud for Cepheid variables, whose absolute magnitude is connected with their period in a known way: this method of finding distance has been described in Chapter III. The astronomer photographs a star cloud repeatedly. Most of the stars will appear the same on every occasion, but a careful search may reveal several

stars—perhaps scores—that are variable. It is, of course, a laborious business to estimate the magnitude of each variable star on each of many plates, in order to find out the period of the several variables; but the labour is rewarded by the determination of the distance of the star cloud.

As examples, we may quote the famous Magellanic clouds. These clouds are near the Milky Way but quite separate from it. They are large enough and bright enough to be seen with the naked eye; both are considerably larger to the eye than the moon, and appear as faint, misty objects. Unfortunately they cannot be seen from most northern stations; they are best seen from stations well south of the terrestrial equator, where they are summer objects (conspicuous in January evenings). The clouds are aggregations of faint stars, it is estimated that there are half a million stars brighter than the eighteenth magnitude in the small cloud. Both clouds contain typical Milky Way objects, such as O and B type stars and nebulæ (clouds of gas). There are five globular clusters in the large cloud as well as open clusters. As both clouds contain Cepheid variables it is possible to calculate their distances; the large cloud is distant 35,000 parsecs, and the smaller about 32,000 parsecs. The size of the large cloud itself is about 4000 parsecs in diameter, the smaller having a diameter of about half that of the greater. You could easily put England and Wales in the United States of America; and you could just as easily pop the whole local system of naked eye stars into the larger Magellanic cloud without noticing any difference. Barring an occasional object which by its great size makes a great beacon, such as these clouds, the naked

eye sees very, very little of the galaxy—even although the naked eye sees a sixth (apparent) magnitude giant when it is a thousand parsecs away. The majority of the naked eye stars are, of course, much closer.

It is easier to locate definite condensations, such as clouds and clusters, within the galaxy, than it is to map the confines of the galaxy itself. For one thing there is a lot of obscuring material and confusion between the bright clouds and clusters all concentrated in the galactic plane.

Investigation of the proper motions of nearby stars had led to the discovery that they show a preference for streaming in two particular directions, but these two streams are now supposed to be local phenomena—eddies in the great movements of the galaxy as a whole, which has been found to be rotating slowly. Rotation is a hard thing to determine; uniform rotation almost an impossibility. One can be very sure that a top is spinning—but that is because one is in a room which is not spinning with the top. The whole system, room plus top, does not show uniform rotation, and what one observes is the *differential* rotation between the top and the room. The daily rotation of the earth would be very difficult to determine if it were not for the difference between the local system, in this case the earth, and its surroundings, the stars, which do not share the rotation. I say difficult, but not impossible, because, of course, Foucault's pendulum (or any gyroscope) *does* show the rotation. As for the annual rotation of the earth round the sun, even a gyroscope could not disentangle that from the diurnal motion; but here again the *differential* motion between sun and stars shows the earth's annual rotation clearly. It would be possible

to calculate the rotation from the movements of the planets without the help of the fixed stars, given a knowledge of dynamical theory and given the sun's mass and all the parallaxes involved, the differential motions between one planet and the next being sufficient to establish all the *absolute* rotations, relative to fixed stars. All these points about differential rotation and absolute rotation are very relevant to the rotation of the galaxy. There is a meaning in saying that the galaxy rotates (without saying relative to what frame of reference it rotates) although it may be very difficult to see the rotation and measure it.

If the galaxy were rotating in one piece—like a wheel—we would not be able to detect the motion. A colossal Foucault pendulum, to be watched for thousands of years, is out of the question. But if the galaxy is rotating bit by bit, each ring of galactic population going on its own orbit, we will be able to detect differential motion between the different annuli. A ring of stars nearer the centre than we are might show a differential velocity compared with our ring. This effect has been looked for among the radial velocities of distant stars, and has been found. The distant type stars exhibit radial velocities which have been analysed statistically, and which show that different rings in the galaxy go round at different rates. A similar analysis of the K stars' radial velocity shows nothing at all. They are too close, and they all drift round with us. According to the analysis of the B stars' radial velocities, the centre of rotation is distant 10,000 parsecs from the sun; and the rotation at this distance from the centre is such that it would take us about 122,000,000 years to get halfway round the galaxy.

We have already mentioned, in an incidental way, the nebulæ, but they deserve special treatment of their own, to which the rest of this chapter will be devoted. In various places in the sky diffuse clouds of faintly luminous matter can be seen with the aid of a good telescope. Some of these patches are bright enough to be seen with the naked eye—to which they appear to be a single star. One of the conspicuous stars in Orion is a nebula when examined with a telescope. Its appearance is very striking; there is a photograph of it on Plate VII. Photographs of nebulæ are better than their actual telescopic appearance, as they are too faint to be striking to the eye, registering the light as it falls; but a photograph stores up the cumulative effect of all the light which falls upon the plate for as long as one cares to expose it, and after three hours exposure, say, a good clear image of a faint object can be built up.

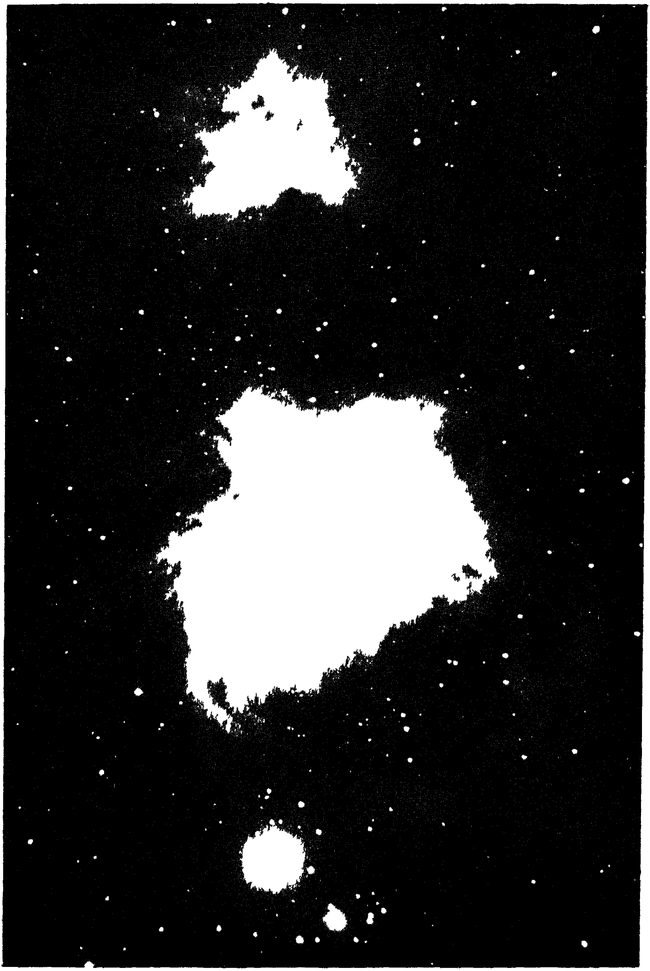
The nebulæ can be divided into two classes: the galactic nebulæ and the extra-galactic nebulæ, the latter having nothing to do with our galaxy, but simply other galaxies, far out in space—so far out that they may look quite small. Taking the local or galactic nebulæ first, they are Milky Way objects. About two hundred of them are known. More than half of the galactic nebulæ are so-called planetary nebulæ, the name being given to them because they show a disc, like a planet. They are shells of gas illuminated by a star in the middle—which has presumably ejected the cloud. These objects are, in some cases, quite near to us—astronomically speaking. That is to say, a few of them are near enough to show a measurable trigonometrical parallax. The nearest has a parallax of $0''\cdot040$, and is therefore " only " 25 parsecs away. It is $12'$ in diameter,

so that the diameter of the object bears the same ratio to the radius of the earth's orbit as 12 minutes of arc to four hundredths of a second—or 18,000 to 1. This cloud of gas is enormously greater than the whole solar system, as far out, at any rate, as we know anything about the planets, Pluto being 39 astronomical units away from the sun. The solar system could rattle about inside this nebula like a pea in a bandbox. This value of the diameter, 18,000 astronomical units (the "astronomical unit" being the mean radius of the earth's orbit round the sun), is fairly typical of planetary nebulæ as a whole.

The other galactic nebulæ are irregular clouds of gas illuminated by nearby stars. They are much larger than the planetary nebulæ, the Orion nebula being about 3 parsecs across. (One parsec = 206,265 astronomical units = 19,160,000,000,000 miles.) There are similar patches of gas that are not illuminated at all, and we only know of them since they obscure faint stars distributed everywhere else in the sky, but avoiding a few well defined areas, which we take to be occupied by black clouds. The Coal Sack, near the Southern Cross, is the best naked-eye example. While most of the matter in our galaxy has been gathered together into compact masses, having about the same mass as the sun, which are the stars, some great clouds of tenuous matter seem to have been left out—unless they have been blown out of the stars later, as a whale spouts water. These clouds, truly gigantic in their extent, lie in great patches in the Milky Way, sometimes illuminated by the light of neighbouring stars, and sometimes dark. It is these objects which can most truly be called nebulæ. It is very probable that they

N

W



E

L 846

THE GREAT NEBULA IN ORION

From a photograph taken at the Royal Observatory, Greenwich, December 1, 1899

Facing p 124

are extremely diffuse—far more diffuse than the giant M stars like Betelgeuse. The density of the Orion nebula is estimated from the velocities of different parts of the nebulæ, determined spectroscopically from the Doppler Effect. These appear to indicate that the nebula is rotating, presumably under the influence of its own gravitational field. Application of dynamical law gives the mass inside any particular circular orbit. The volume, of course, we know from direct observation and from the parallax. It appears that the whole nebula contains enough matter to build ten thousand suns, but that it is spread out over so vast an area that the density is one million billionth of the density of the air on the earth's surface.

The extra galactic nebulæ are very different objects. The most conspicuous of them is visible to the naked eye as a fourth magnitude star in Andromeda. Examination with a telescope shows that the nebula really extends over three degrees in diameter, the central portion being all that is seen with the naked eye. This nebula is a colossal aggregation of stars; it is, in fact, a galaxy of its own, complete with variable stars and even Novæ. Observations of the Cepheid variables in this nebula fix its distance fairly accurately, just as in the case of the Magellanic clouds. But the Andromeda nebula is very much farther from us than these clouds, which, it will be remembered, are about 35,000 parsecs away, the nebula being 270,000 parsecs distant. It is perhaps worth stating that 270,000 parsecs = 5,130,000,000,000,000,000 miles—and that the Andromeda nebula is the nearest of the extra galactic nebulæ. It is, of course, an enormous object. Recent researches have shown that it is roughly comparable in size with

our own galaxy. Generally speaking, stars occur in great disc-shaped aggregations, slowly rotating. All the naked-eye stars that we can see, and all that vast multitude of stars too far off to be seen individually, but taken together giving out enough light to shine in a great girdle round the sky as the Milky Way, are the galaxy in which our sun finds itself—an inconspicuous member. Space is large enough to hold similar galaxies elsewhere; the nearest of these is near enough to appear to the naked eye, which is quite unable to resolve this far off object into its component parts, as a single star. Studied minutely with the largest existing telescopes, the true nature of this remarkable object has become apparent. Nor, indeed, is this second galaxy by any means the only companion to our own. There are literally hundreds of thousands of other galaxies. Just as the sun is only one member of a galaxy of stars, so is the galaxy only one member of a super-galaxy of galaxies.

Astronomy has not yet found a super super-galaxy of super-galaxies, but some such arrangement is easily conceivable. Nothing can stop this piling up of aggregation of aggregations, unless it is the Relativity theory, which has already established that *the* speed record, never to be broken, is the velocity of light, and may presently establish as a reality the suggestion which has already been propagated that there is after all a limit to the amount of matter which space itself can hold. We tread here upon controversial ground. But the extra galactic nebulæ are real enough, and their nature as galaxies in themselves is now fairly established beyond serious question.

These objects *avoid* the Milky Way. That they should

L 846

THE GREAT NEBULA IN ANDROMEDA

From a photograph taken by C. W. Ritchey at the Yerkes Observatory, September 18, 1901

Facing p 126

not tend to distribute themselves near to it is to be expected. They have simply nothing to do with the particular plane in which our galaxy chooses to orient itself. They appear to avoid the Milky Way because we cannot see any extra galactic objects through the middle of our own galaxy, as there is too much obscuring matter. This distribution is in itself a proof of their extra-galactic character. Things which do not cluster round our galactic plane are either very close—like K stars—or very distant. The close objects like K stars are distinguished from the distant objects by appearing *in* the Milky Way as well as outside it—in the Milky Way they are seen in front of the other galactic objects. The extra galactic nebulæ are not seen in the Milky Way because they are behind the galactic matter, and outside the galaxy.

There are thousands of these extra galactic nebulæ; they are presumably all the same size—or about the same size; and naturally those that are farther off look smaller than the Andromeda nebula. By studying their apparent sizes we can arrange them in order of their distance from us. Perhaps the most striking features of the galaxies (once one is accustomed to the idea that they *are* galaxies their immense sizes and immense distances from us are not to be wondered at) are their spectra, which are like those of G stars—a sort of average of the millions of members of all types—but which all show red shifts. For example: the yellow sodium lines which are a feature of G spectra are present in extra-galactic nebular spectra, but instead of their appearing in precisely the right shade of yellow they appear a little redder than terrestrial—or solar—sodium lines. To speak technically, the wavelengths

of the absorption lines in these nebular spectra are all a little longer than the wavelengths of corresponding lines in terrestrial sources. This shift of the lines is exactly like a Doppler shift, and might be interpreted as showing that the galaxies are all going away from our galaxy. So far, so good; but here is the interesting thing: the farther off the galaxy, the bigger the red shift, and the faster it appears to be going away from us. The red shift is proportional to the distance from us; the speed of recession is 550 kilometres per second per megaparsec. (One megaparsec = one million parsecs.) That is to say that a nebula one megaparsec away from us will have a red shift corresponding to a speed of 550 kilometres a second; a nebula ten megaparsecs away has a speed of 5500 kilometres a second, and so on. The farthest nebula which has been observed as yet is about fifty megaparsecs away; its red shift indicates a retreat from us at the rate of 15,000 miles a second—nearly one-tenth of the velocity of light.

The very word megaparsec is worth our attention. I suppose that when the late Professor Turner invented the parsec of 19,160,000,000,000 miles it was generally felt that here, at least, was a unit of length truly appropriate to deal with astronomical distances—for which the statute mile was clearly unsuited, and for which even the "astronomical unit" of 92,900,000 miles (the mean radius of the earth's orbit round the sun), useful enough in describing planetary motions, was unsuitable. But the parsec is a very convenient unit for describing "local" phenomena, the nearest naked-eye stars being anything like half a dozen or a dozen parsecs away. But the parsec itself is too tiny a unit to be a convenient measure of the distance when

we are talking about the extra-galactic nebulæ, and the megaparsec has quietly stepped into its place.

The Andromeda nebula is 0·27 megaparsecs away; this distance is such that light, which travels at 186,000 miles a second, takes 880,000 years to cover the course. We do not see the Andromeda nebula as it is now, nor will we ever, nor will our children's children. We see what it was like 880,000 years ago. In the remote past, a Nova appeared; the astronomers of the future will see one of the tiny star images of their plates brighten from one day to the next. The astronomers of the present determine the period of a Cepheid variable in the nebula. They are watching the behaviour, day by day, of something that *was* a Cepheid 880,000 years ago. It may be one still, for all we know. (There is a fair chance that our successors will find out, for the earth seems to be some ten thousand million years old, and it is usual to suppose that since the sun is near the middle of the spectral sequence it is about halfway through its career. But we have again been led into controversial ground: the evolution of the stars through the spectral types is not yet firmly established.)

This general movement of the extra-galactic nebulæ away from our galaxy is the expansion of the universe, now a matter which is being actively discussed among our theoretical astronomers. We may content ourselves with remarking that at some time in the past, the galaxies were all much closer together than they are now, and probably interpenetrated one another, and that it is natural to suppose that this interpenetration was in some sense the origin of the universe, but it is by no means necessary to suppose this. The galaxies may be older than that, and have fallen together before

they drifted apart, as they are still drifting. The other point to notice is that the motion appears to be quite outside Newtonian dynamical law, the application of which *within* the galaxy is nearly universal.

I do not know what more to say about the galaxies. I can only invite you to contemplate this vast, elaborate system of systems, which appears to be in the act of breaking up for good and all. But for all the expansion of the universe, we shall always be left with our own galaxy, our naked-eye stars and our Milky Way, and our fellow planets to cheer the earth on its ceaseless journey round the sun. Ultimately the sun will burn up all its resources and a cold earth supporting no life will go on circling round its cold remains, long after the end of the world to mankind—unless that end is brought about by a collision between the sun and another star. These things are no affair of ours, except in the imagination. For anything that astronomy can tell us, thousands of millions of years have still to elapse before the end of the world.

CHAPTER VII

Observatories

THE oldest observatory that is still in active existence is the Vatican Observatory, founded in the sixteenth century by Pope Gregory XIII, the reformer of the calendar. Next in order of foundation is the observatory of Leiden University, which was founded in 1633. This was situated, originally, on the roof of the University building, and the equipment consisted of a single quadrant, which had originally belonged to Snellius, the professor of mathematics at the University. His successor, Jacobus Golius (or Jacob van der Gool), persuaded the University authorities to take over the instrument and build an observatory for it. Golius made a particular study of Arabic, and indeed became Professor of Arabic. In those days the Arabians had carried the study of mathematics and astronomy further than any other people, and their pre-eminence was such that Golius chose as the subject of his inaugural lecture the desirability of combining the studies of mathematics and Arabic. Within a few decades, however, the mathematicians of Western Europe surpassed by far their Arabian predecessors, and Golius' advice was to become profitless. Leiden Observatory continued in a small way until its re-organization in 1861. The great French astronomer,

Lalande, said, "En 1774 je n'y vis ni Astronome ni instrumens que l'on puisse citer." The observatory was moved to a new site in 1861 and is now a very active centre of astronomical research. Other seventeenth-century observatories still in active existence are, Utrecht University Observatory (1642), Copenhagen (1656), the Observatory in Paris founded by the Académie des Sciences in 1667, and the Royal Observatory at Greenwich (1675).

The Royal Observatory at Greenwich was founded by Charles II for the purpose of assisting navigators in the problem of determining the longitude of a ship at sea. It still maintains a direct connexion with navigation, and is responsible to the Admiralty, who are charged with its maintenance. The first Astronomer Royal was the Reverend John Flamsteed, who conducted a great number of observations of the positions of fixed stars and planets. Although Flamsteed was a very diligent observer, he was considered to be a very unsatisfactory Astronomer Royal by his contemporaries, Isaac Newton and Halley, as he consistently refused to publish the results of his observations. He wished to wait until they were complete, and was perhaps afraid that Newton would make some magnificent deduction from the half-completed observations and rob their author of the credit due to him. Newton persuaded the Royal Society to institute an inquiry into the affairs of the Observatory; one result of this inquiry was that Flamsteed deposited a sealed volume of his results with the Society, as an earnest of his good faith and of his work performed; the seal was only to be broken after Flamsteed had revised all the observations. Halley broke the seals immediately;

this embittered the contending parties. A relic of Newton's intervention on this occasion is the Annual Visitation of the Royal Observatory by the President of the Royal Society and a special Board of Visitors, which continues to this day.

King Charles' fit of expansive generosity in founding the Observatory did not extend to providing Flamsteed with instruments, which he had to find for himself, and when he died his widow reclaimed them; this is very unfortunate, as the instruments have since been lost, while all later ones have been preserved. The Observatory still possesses many of the instruments used by Flamsteed's successors.

The original observatory building is well preserved; it was built in the form of an octagon, with large windows facing north, south, east and west. The early astronomers observed out of the window. Their observations of right ascension and declination were essentially the same as those carried out to-day with a modern transit circle; the old observations were of course very considerably less accurate.

When Flamsteed died he was succeeded, as Astronomer Royal, by his old adversary, Halley, who is, perhaps, best known for his work on comets. He was the first astronomer to predict the return of a comet. Although these bodies are bound to the sun in the same manner as the planets, their orbits are so highly elliptical that they are only near enough to the sun (and the planets, like our earth) to be visible for a small part of their orbit; away from the sun they become lost to view. Halley's comet was observed by him on a sufficient number of occasions for him to calculate the comet's orbit and predict its next

reappearance—which occurred long after Halley's death. The next Astronomer Royal was Bradley, who discovered the nutation of the earth's axis (p. 35) with a long zenith telescope which still hangs in an honoured position—but, alas, rusty and unusable—on the walls of the Royal Observatory.

Greenwich has continued to expand up to the present day. The Observatory maintains the time service of Great Britain. Special observations of star transits for time determination are made nightly (when the weather permits) with a small reversible transit circle fitted with a moving wire micrometer (p. 22). The time is determined with a probable error of only one hundredth of a second. Two fundamental clocks, kept in a cellar which is maintained at a constant temperature within a quarter of a degree Fahrenheit, record the sidereal time. A third clock keeps Greenwich mean time. This third clock is used to broadcast radio time signals, the familiar six pips on the wireless, which are simply the last six beats of the pendulum in every fifteen minutes. As the pendulum beats a contact is made on an electric circuit, and the resulting electric signals are sent up to Broadcasting House on a telephone wire. A more accurate signal for scientific purposes—navigation and survey—is sent out from a separate clock which beats *sixty-one* times in a minute. The field surveyor compares the beats of his chronometer, beating sixty times a minute, with the sixty-one standard beats. If this chronometer is exactly right, his seconds beats will coincide with the 1st, 61st, 121st, &c. radio beats; but if he is one-sixtieth of a second fast his beats will coincide with the 2nd, 62nd, 122nd, &c. By counting the

number of the radio beats with which the field chronometer's beats coincide the observer can tell the error of the chronometer to one-sixtieth of a second. There is a chance that the radio signal will be sent out wrong —by a twentieth of a second, or so. It is accordingly received at Greenwich and compared with the standard sidereal clocks. At the end of each month the star transit observations are collected together and the behaviour of the standard clocks is carefully analyzed, so that corrections to the last month's radio signals can be determined. They are then published in the Admiralty's "Notices to Mariners"—though it is to be feared that those mariners who have been misled by incorrect radio signals will have piled up their vessels on the rocks long before the "Notices" are published! Actually the radio signals are never in error by as much as $0^s{\cdot}05$, which is only a few feet on the surface of the earth; and mariners who steer as close to rocks as all that on the strength of their own astronomical observations deserve what they get.

Besides the small transit for time, Greenwich possesses a great transit circle. This is a worthy old instrument, built to the design of Sir George Airy, then Astronomer Royal, in 1850. It is used for observing the right ascensions and declinations of the sun, moon and major planets, and for making great catalogues of the positions of stars down to the eighth magnitude. Greenwich is one of the few observatories which continue to observe the moon's position. The sun, of course, is subject to two sorts of observations; physical observations of sunspots, and of the solar spectrum, on the one hand, as compared with transit observations of the sun's right ascension and declination on the other, from which

the position of the equinox, fundamental to the calendar and the seasons, is deduced. The positions of the moon and major planets are still wanted for navigation. In addition, the observation of Venus helps to determine accurately the equinox.

Observations of the separation and relative positions of double stars are made at Greenwich with the old Great Equatorial. This is a large refracting telescope with a lens twenty-eight inches in diameter and a focal length of twenty-eight feet. It is one of the largest refractors in existence (the largest has a lens of forty inches diameter, and is at the Yerkes Observatory, near Chicago). The positions and separations of the stars are measured by a pair of wires in the eyepiece of the telescope; one wire is placed over each star; the distance between the wires is then a measure of the angular separation of the components of the double star. Long continued series of observations of this kind determine the orbits of the double stars, and the application of Newtonian mechanics then yields the masses of the two stars.

Greenwich possesses a pair of telescopes mounted on a single axis, perched on top of the administrative building. One is a reflector with which colour temperatures are measured in the manner described in Chapter IV, and the other is a reflector which is used for the measurement of parallax. For an elderly observatory Greenwich holds its head high among the astronomical centres of the world, though its telescopes cannot compete in size with the world's greatest telescopes in Canada and the United States of America. Cambridge and Oxford both possess astronomical observatories, but not so elaborate as Greenwich.

There used to be an observatory on top of the Great Gate of Trinity College, Cambridge. It was little more than the private observing place of the professor of astronomy at the University, and must have resembled the observatory at Leiden.

The Admiralty maintains a sister observatory to the Royal Observatory at Greenwich at the Cape of Good Hope. This observatory has played a very important part in the mapping of the southern skies, and the determination of parallax, proper motion and radial velocities in the southern constellations, inaccessible to northern telescopes. In former days the Cape was of extreme importance to navigators; but the cutting of the Suez canal has diminished the number of vessels calling at Cape Town, and the invention of wireless telegraphy has done away with the necessity for calling at a port in order to set a vessel's chronometers right. The time determined at the Cape observatory is broadcast from a local station.

Turning from these observatories typical of the old world (though we have by no means exhausted the list, even of British observatories), we consider next the observatory which possesses the world's largest telescope—Mount Wilson Observatory, in Pasadena, California. This observatory is built at the top of a mountain and is nearly 6000 feet above sea level. There is of course less atmospheric absorption on top of the mountain than down below, and so it has been over and over again worth while to haul the telescopes and equipment up a narrow road on the precipitous sides of the great mountain, in order to get better conditions at the top. Mount Wilson was originally a solar observatory, and as it was started in 1904 before

the widespread use of automobiles the first instruments were taken up bit by bit on mule back. The first instrument was the Snow solar telescope, of the heliostat type, in which the telescope proper lies still and waits for the sunlight to be fed into it by a moving mirror driven by clockwork. The sun's radiation was first measured with modern precision on Mount Wilson. Some years later it was decided to build a great reflecting telescope and to erect it on the top of the mountain. This telescope is sixty inches in diameter—nearly twice as great as any telescope in Britain—and has performed, and is still performing, excellent service. A picture of it is shown in Plate IV. The telescope consists of an open-work tube. At one end of this is the great reflecting mirror, and at the other end is a secondary mirror; this latter end points to the star whose light is to be collected. The observer may work either at the Newtonian focus, at the open end of the tube, or, by changing the secondary mirror, at the Cassegrain focus at the butt end. The picture shows a spectrograph attached at the Cassegrain focus; the prisms in the spectrograph can be seen very clearly. The whole telescope swings in a giant yoke. Keeping the yoke fixed the telescope moves in declination. It is moved until it has the same declination (this is the angle between the direction of the telescope and the direction of the North Pole of the heavens) as the star whose spectrum is to be examined. The yoke is mounted in a bearing in which it can rotate about an axis parallel with the earth's axis, so that the whole telescope can be moved from one right ascension to another. When the telescope has been set to the star's right ascension a great clock drives the axis

round to follow the star. The observer watches through a special device to see that the telescope is being driven accurately by the clock, so that the star image remains on the slit of the spectrograph; if the star runs off the slit, on account of any imperfection of the clock drive, the observer speeds up or slows down the motion of the telescope with a hand control. His night's work will consist of setting the telescope on the stars in his programme and exposing a photographic plate in the camera of the spectrograph for a suitable time (depending on the magnitude of the star). Throughout the exposure, he must guide the telescope. The spectrograph can be removed and an ordinary plateholder put in its place. The telescope is then itself a great camera, and takes direct photographs of the stars—for parallax and proper motion, or to find out the details of the structure of nebulæ.

These remarks apply almost equally well to the younger but larger brother of the 60-inch, which is 100 inches in diameter; the largest that has yet been completed, though progress has been made with the construction of a two-hundred inch mirror and telescope. The great advantage of so large a telescope is not in its magnifying power but in its light grasp. All the light that falls on this enormous disc is concentrated on to one tiny focus; and with the hundred-inch telescope one can photograph very faint objects. It is with this telescope that the red shifts of the spectra of the extra galactic nebulæ have been studied; but the telescope has also been the means whereby an enormous corpus of other astronomical observation have been secured. There is a large staff of astronomers at Mount Wilson, who work on the giant telescopes in rotation. Each

astronomer takes each instrument for a few nights in each month; and in this way the instruments are put to the maximum use, and are used as nearly as possible one hundred per cent of the available time from sunset to sunrise on every clear night; and there are many clear nights in the year in southern California.

These very large telescopes are all reflectors. There is another giant reflector, seventy-two inches in diameter, at the Dominion Observatory at Victoria, British Columbia, and several more are being erected in various parts of North America, while the largest refracting telescope—the type of telescope most familiar to the public, with a lens in the front of it—is only forty-two inches in diameter. No attempts have been made recently to make a larger lens. To begin with, it is easier to make a giant mirror than a giant lens. To cast a very large block of glass is very difficult; and the interior quality of the glass (freedom from small bubbles, and clearness) does not matter so much if the glass is to be made into a mirror as it does if the glass is wanted for a lens. Only one surface has to be accurately ground for the mirror, and two for the lens. Again, a single lens suffers from a great disadvantage in that it focusses the several colours at different foci, the red being less refracted than the blue; so that if you focus the star accurately for the blue light the red is out of focus. To combat this chromatic aberration, as it is called, the standard optical device is to employ a pair of lenses, one convergent and one divergent, and play the chromatic aberration of one against that of the other. In this way one can make an achromatic lens, focussing all the colours at the same point, more or less—the achro-

matism is never quite perfect. But this means casting two glass discs and grinding four surfaces with great accuracy. In short, the technical difficulty of casting and shaping the lenses is very great. This difficulty is reflected in the cost. The mirror is achromatic as it stands, and no colour correction is necessary. Modern practice in building large telescopes—three feet or more in diameter—seems to have adopted as standard the reflecting telescope, particularly if the instrument is to be used with a spectrograph. It is claimed that refractors give better images and are more suitable for parallax work.

The cost of conducting astronomical research is very great, and it is borne in a number of ways. In the Old World the observatories are nearly always associated with the universities, and the professional astronomers make their living, at least in part, by teaching. There are exceptions; most nations support a national observatory, such as Greenwich, which combines the maintenance of a national time service and the care of navigational astronomy with its more purely scientific functions. Canada maintains at Victoria a Dominion observatory which is entirely devoted to disinterested research. When we come to the United States, which is at the present time the great stronghold of scientific astronomical observation, most of the great observatories, as well as a host of small but competent ones, are connected with universities and colleges, but the telescopes have usually been presented to the institution by a particular benefactor; a good example is the Lick observatory of the University of California, which commemorates the name of its original donor. A notable exception to the general rule is the great Mount Wilson

observatory which is not connected with a university, but with the Carnegie Institute of Washington. The United States maintains a national naval observatory at Washington, which is used exclusively for navigational astronomy in the sense of charting star positions with a transit circle and maintaining a time service which is broadcast from Annapolis.

No other line of human inquiry demands so great a financial outlay with so little expectation of economic return as the investigation of the outer galaxies, which can only be carried on with large and expensive telescopes. It is fortunate for the progress of scientific inquiry that the need for the money to build such expensive instruments has been met by the imagination of the rich men of America. Nor should it be forgotten that the largest instruments in Great Britain have been presented to the various observatories which make use of them by private individuals who have felt that the pursuit of astronomical knowledge for its own sake was a worthy object of their benefactions.

INDEX